Journal Pre-proof

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PII: S0032-0633(20)30350-0

DOI: https://doi.org/10.1016/j.pss.2020.105137

Reference: PSS 105137

To appear in: *Planetary and Space Science*

Received Date: 1 April 2020

Revised Date: 6 November 2020

Accepted Date: 9 November 2020

Please cite this article as: Moore, K., Courville, S., Ferguson, S., Schoenfeld, A., Llera, K., Agrawal, R., Buhler, P., Brack, D., Connour, K., Czaplinski, E., DeLuca, M., Deutsch, A., Hammond, N., Kuettel, D., Marusiak, A., Nerozzi, S., Stuart, J., Tarnas, J., Thelen, A., Castillo-Rogez, J., Smythe, W., Landau, D., Mitchell, K., Budney, C., Bridge to the stars: A mission concept to an interstellar object, *Planetary and Space Science*, https://doi.org/10.1016/j.pss.2020.105137.

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Bridge to the stars: A mission concept to an interstellar object

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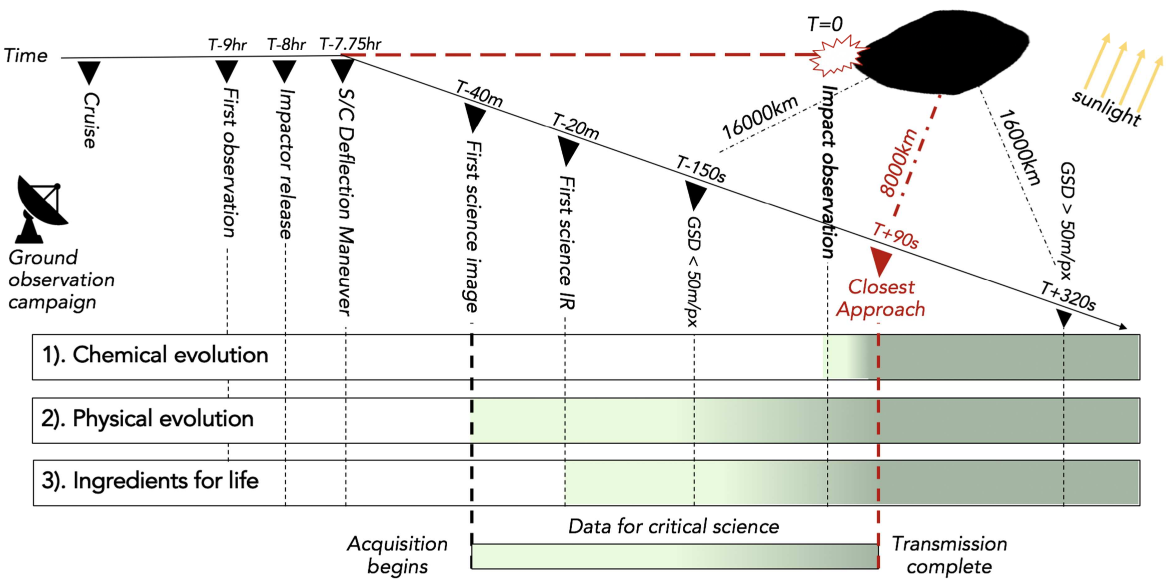

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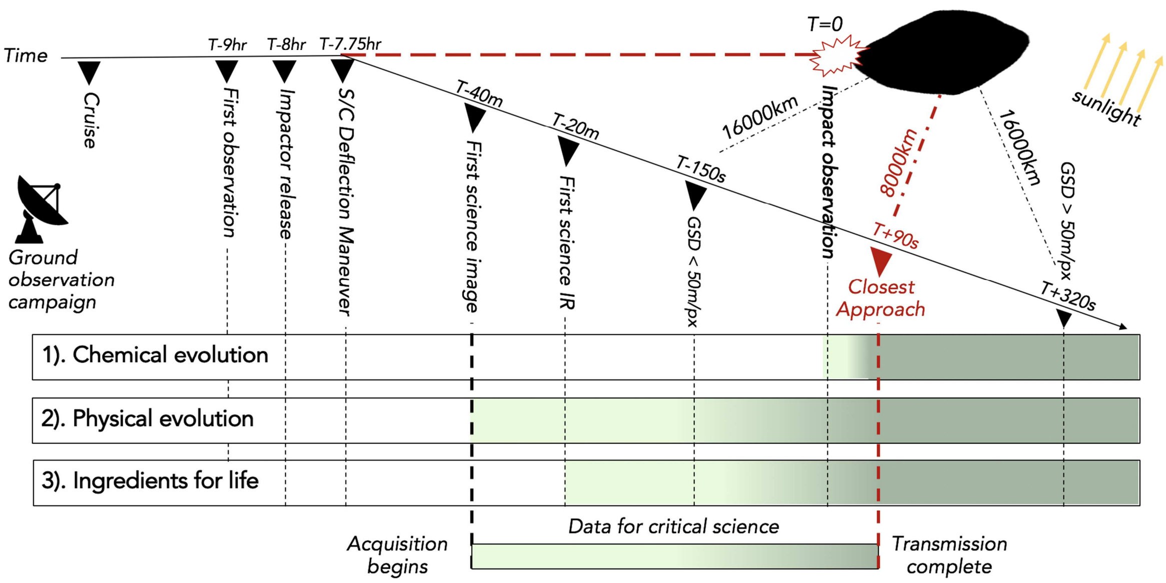
overies since the mid-1990’s have revealed an astounding diversity of planetary systems. Studying these systems is essential to understanding planetary formation processes, as well as the development of life in the universe. Unfortunately, humanity can only observe limited aspects of exoplanetary systems by telescope, and the significant distances between stars presents a barrier to *in situ* exploration. In this study, we propose an alternative path to gain insight into exoplanetary systems: Bridge, a mission concept design to fly by an interstellar object as it passes through our solar system. Designed as a New Frontiers-class mission during the National Aeronautics and Space Administration (NASA) Planetary Science Summer School, Bridge would provide a unique opportunity to gain insight into potential physical, chemical, and biological differences between solar systems as well as the possible exchange of planetary materials between them. Bridge employs ultraviolet/visible, near-infrared, and mid-infrared point spectrometers, a visible camera, and a guided impactor. We also provide a quantitative Monte Carlo analysis that estimates wait times for a suitable target, and examines key trades between ground storage and a parking orbit, power sources, inner versus outer solar system encounters, and launch criteria. Due to the fleeting nature of interstellar objects, reaching an interstellar object may require an extended ground storage phase for the spacecraft until a suitable ISO is discovered, followed by a rapid response launch strategy. To enable rapid response missions designed to intercept such unique targets, language would need to be added to future NASA announcements of opportunity such that ground storage and rapid response would be allowable components of a propose



d mission.

1. Introduction

The detection of exoplanets has revealed a surprising diversity of solar systems within the Milky Way galaxy. Some stellar systems, e.g., those with gas giants orbiting closely to their host star, deeply contrast our own Solar System. Such systems demonstrate that the processes of planetary formation, migration, and evolution are still not well understood and may not be the same throughout the galaxy. Examination of materials present in exoplanetary systems--their mineral, isotopic, and molecular chemistries--can reveal the physical conditions under which they formed and thus provide critical insights into extra-solar system formation. By tracing the history of organic molecules through their cycles of formation and modification, from the surfaces of tiny dust grains within molecular clouds to their incorporation into planetary systems, we can improve our understanding of where and in what forms the raw material for life might exist. Yet current telescopic spectral observations of exoplanets provide an incomplete picture of the basic elemental compositions in exoplanet systems. To distinguish between the array of theorized scenarios for solar system formation and the evolution of organic molecules, scientists need detailed compositional information – deuterium/hydrogen and other isotopic ratios, as well as abundances of elements and noble gases – that can only be obtained from in situ measurements.

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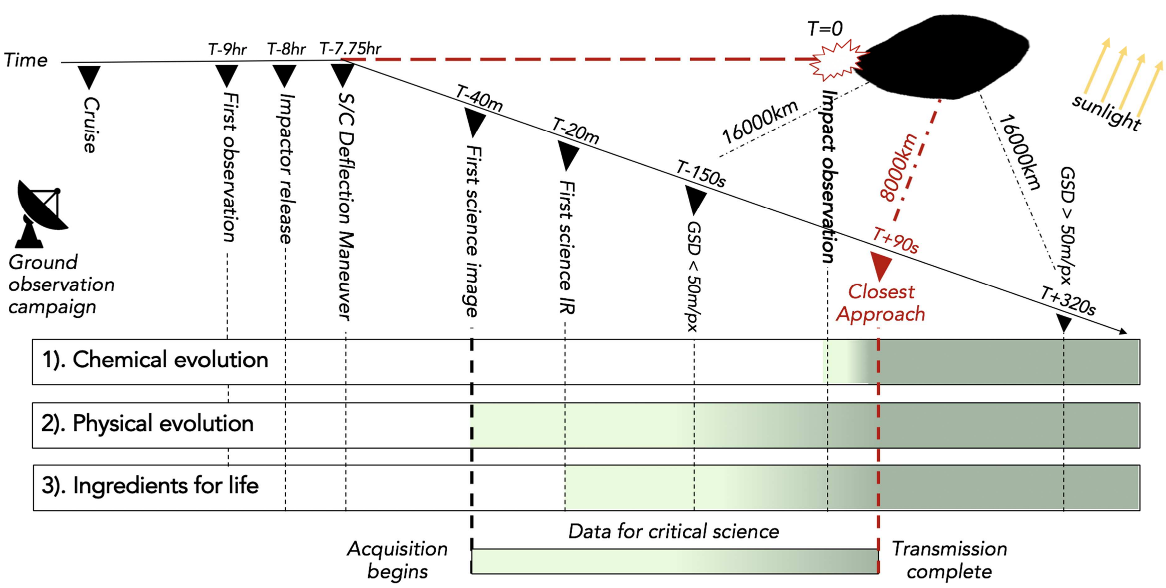

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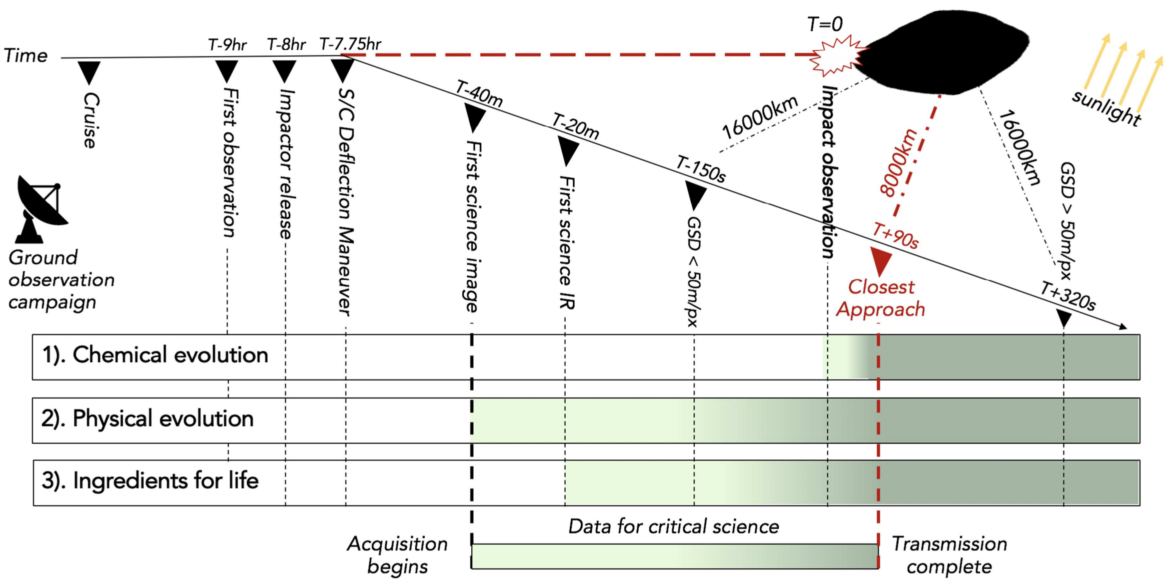
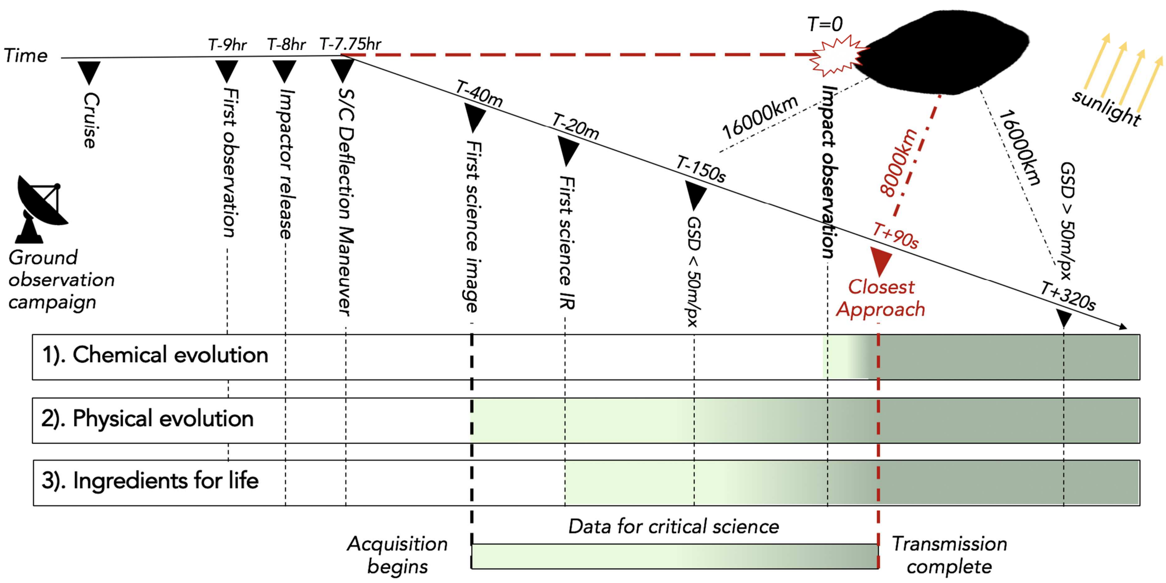
to an exoplanetary system would provide crucial insight into planetary formation processes throughout the galaxy, as well as the origins of life, questions deemed high priority in the decadal survey, *Visions and Voyages for Planetary Science in the Decade 2013-2022* (National Research Council, 2011). However, travelling to even the closest star system, Alpha Centauri, is estimated to take hundreds to thousands of years using projections of near-future technological development (e.g. Long, 2011). In this paper we discuss an alternative opportunity: studying interstellar objects (ISOs) – material ejected from exoplanetary systems – as they pass through our Solar System. These objects have the potential to address high-priority topics such as the chemical, physical, and biological processes that shape solar system evolution for diverse star properties.

ISOs are likely planetesimals similar to asteroids and comets in our solar system — the building blocks of planets. These objects may then become ejected into interstellar space, particularly during early solar system formation and evolution (e.g., Laughlin and Batygin 2017. For example, giant planet migration scatters large amounts of material into interstellar space (Tsiganis, 2005). Planetesimals that orbit binary stars can also be ejected into interstellar space from too close of an encounter with one of their host stars (Holman et al., 1999; Cuk 2018, Jackson et al., 2018). Finally, loosely-bounded planetesimals — akin to the predominantly icy bodies in our Oort cloud — may also be pulled into interstellar space by neighboring star systems (Vincke et al., 2016; Hands et al., 2019). Once ejected, these planetesimals may eventually pass thro



ugh our own solar system, delivering extrasolar material directly to our doorstep.

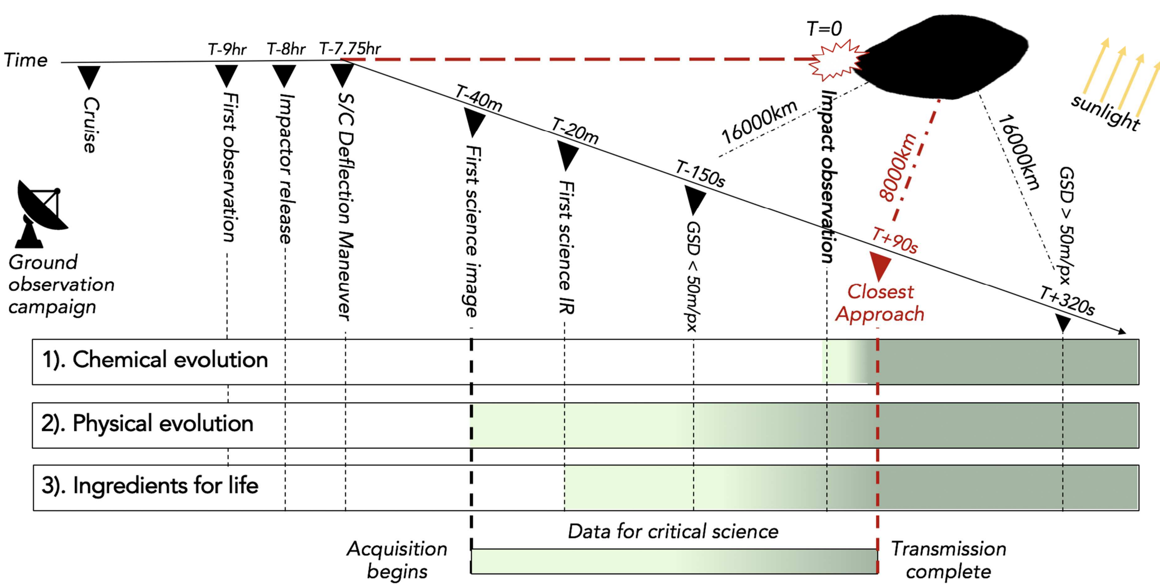
Excitingly, the detection of 1I/'Oumuamua in 2017 (Meech et al., 2017) and 2I/Borisov in 2019 (MPEC-2019-R106) confirmed the presence of ISOs in our solar system (Williams, 2017; Meech et al., 2017). However, telescopic observations of these fleeting objects have left more questions than answers. Although 2I/Borisov fit the expectation that most interstellar objects would be icy bodies (Fitzsimmons et al., 2018) and have a broadly similar composition to known solar system objects (de Leon et al., 2019), in contrast, the composition of 1I/'Oumuamua remains uncertain. Spectroscopic observations primarily suggested a reddish color, which could be either cometary or asteroidal in origin (Jewitt 2017, Masiero 2017, Ye et al. 2017, Bannister et al. 2017, Meech et al., 2017; Fitzsimmons et al., 2018). While non-gravitational cometary-like acceleration was detected (Micheli et al., 2018; Seligman et al., 2019), no spectroscopic evidence of outgassing was directly found (Ye et al., 2017; Fitzsimmons et al., 2018; Park et al., 2018; Trilling et al., 2018). This could suggest that icy interstellar objects develop a thick, insulating mantle that would inhibit outgassing (Jewitt, 2017; Fitzsimmons et al., 2018). Although this hypothesis is at odds with the clear cometary behavior of 2I/Borisov, it could explain why this comet outgasses little water (Yang et al, 2020). Finally, 1I/'Oumuamua's disc-like shape with a 6:6:1 aspect ratio and its excited rotational state are unusual when compared to other objects in our solar system (Mashchenko 2019). Taken together, these observations suggest that interstellar objects are compelling objects that hint at both tantalizing similarities and perplexing differences



between our own solar system and exoplanetary systems. Since a thorough space-based telescopic campaign of 1I/'Oumuamua was insufficient to classify the object in comparison to small bodies in our own solar system (Seligman and Laughlin, 2018), we identify the need to investigate the surface and interior composition of ISOs through measurements from a dedicated spacecraft mission.

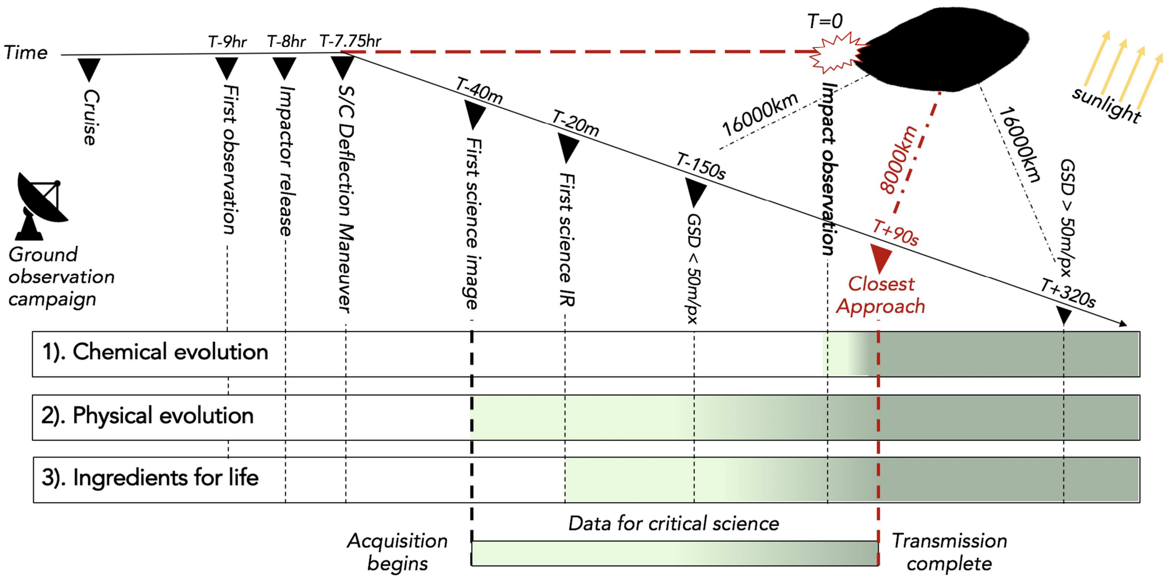
Multiple mission strategies exist to explore an ISO. Hein et al. (2019) and Hibberd et al. (2019) have proposed a multi-year chase to flyby the ISO 1I/'Oumuamua, provided that the mission could be launched in the near future. Alternatively, one could design a mission to encounter a future ISO in the inner solar system, near its perihelion. The European Space Agency's Comet Interceptor has adopted this strategy and will place a spacecraft in the Sun-Earth L2 point with the intention to encounter a future long period comet following discovery (Jones, 2019). By design, the comet interceptor mission could also encounter an ISO in the unlikely event that a reachable ISO is detected while the comet interceptor is waiting. However, the science case for visiting a long period comet is different from that of an ISO. Additionally, since it is not certain that an ISO would display cometary behavior, one cannot assume that a spacecraft designed to encounter a comet would be similarly well equipped to study an ISO. Therefore, we acknowledge the need for a mission concept to explicitly encounter an ISO.

Multiple facilities currently exist for the purposes of surveying the sky, scouting for Near-Earth Objects (NEOs), comets, and possible ISOs. While early studies on the detectability of ISOs predicted a low



number density (Moro-Martin, 2009; Cook 2016; Engelhardt 2017), estimates were elevated to ~0.2 au^-3 detectable ISOs following the discovery and characterization of 1I/‘Oumuamua (Do et al 2018). When future survey telescopes such as the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) become operational, the number of ISO detections should improve to an estimated ~1 per year (Trilling et al., 2017a; 2017b), of which a certain fraction should be reachable by spacecraft. Indeed, Seligman and Laughlin (2018), provide an estimated wait time of approximately 10 years between ISOs reachable by conventional rockets available today. Expanding on Seligman and Laughlin’s work, we present, to the best of our knowledge, the first complete payload design and mission concept dedicated to intercept a yet-to-be discovered interstellar object. Sections 4 and 6 provide an argument suggesting that current to near-future observation facilities should yield target detection rates sufficiently high enough to enable Bridge. Given the expected number of detections, we argue that a mission to an interstellar object would yield valuable science and is technologically feasible.

In this study, we outline a point design for a spacecraft with an instrument suite that is tailored to explore ISOs and is achievable under the budget prescribed in the NASA New Frontiers 4 Announcement of Opportunity (AO) (NASA 2016). We assume that future New Frontiers AOs would have similar constraints. In this article, we first outline the science goals and objectives that Bridge would address as well as their connection to the decadal survey (Section 2), followed by proposing the instruments that are best-fit to accomplish those goals (Section 3). Next, we disc



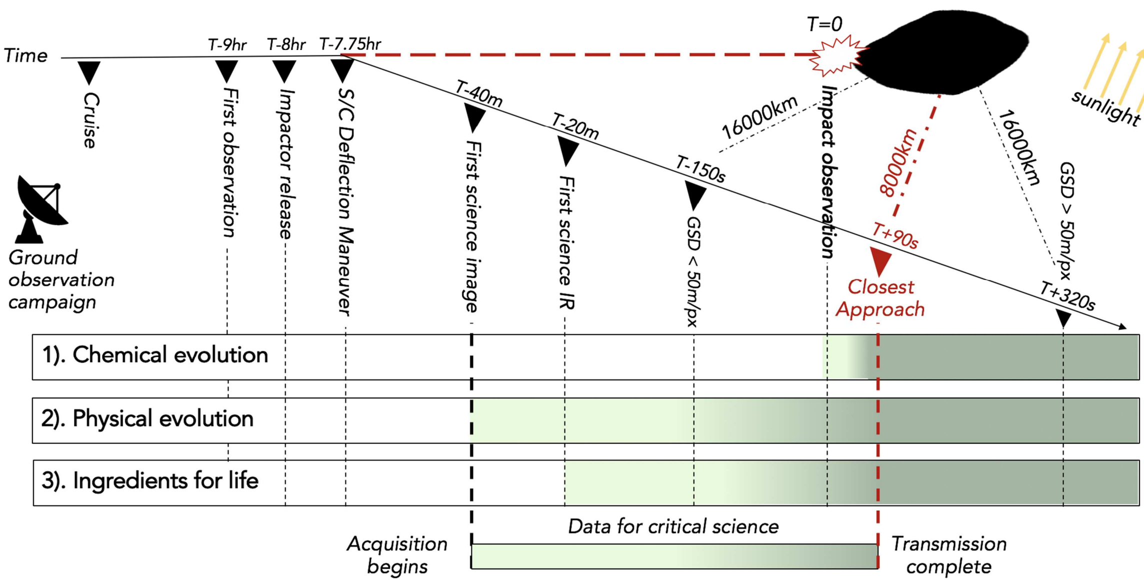
uss the mission design (Section 4) and spacecraft specifications of Bridge (Section 5). Finally, we discuss key trades and conclude with technological advancements and policy changes that would enable a mission like Bridge to an interstellar object (Sections 6 & 7).

2. ISOs as interstellar laboratories

2.1 Bridge Science goals

As a physical sample from another stellar system, an ISO preserves details of solar system building processes that occur elsewhere in the galaxy. Our mission is designed to address two primary science goals related to key themes in the planetary science decadal survey.

Goal A: Determine whether the Solar System evolved like other stellar systems within the Milky Way galaxy. The discovery of exoplanets has fundamentally challenged our understanding of planet formation and migration. While we expect the starting environment of all planetary systems to be a protoplanetary disk, telescopic observations reveal astounding diversity in final physical architectures, of which few are similar to the Solar System (e.g., hot Jupiters; Dawson & Johnson, 2018). This begs the question: do the physical and chemical processes that have shaped our solar system unfold the same way in other stellar systems? And if not, why do these processes diverge; that is to say, why is our solar system unique (NASA, 2018)? An ISO can address this question because it has borne witness to the physical and chemical process

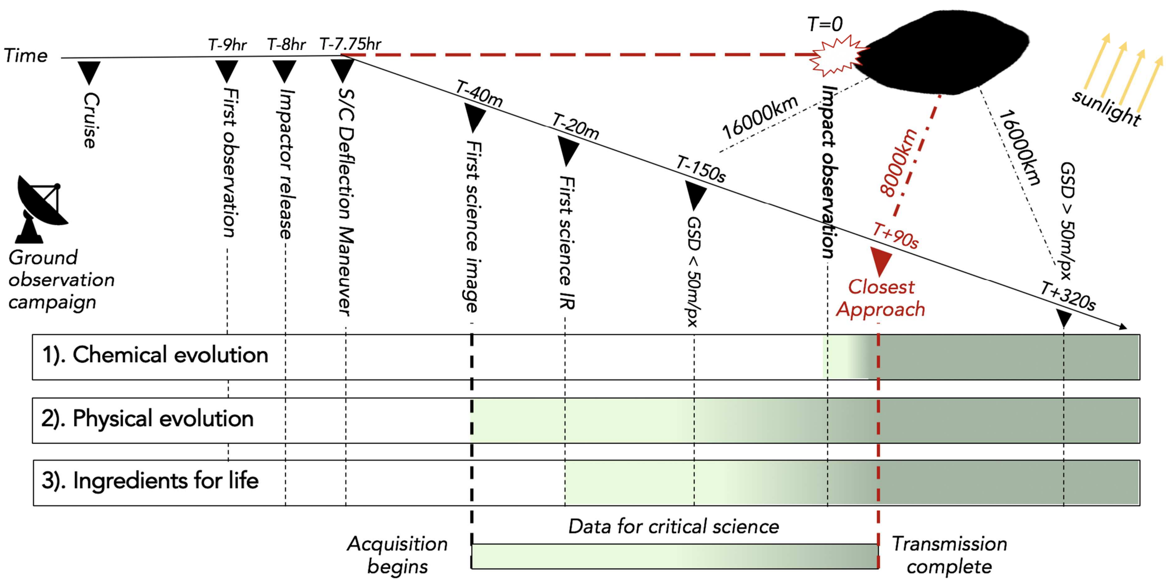


es that gave rise to its home system.

Goal B: Determine whether the basic chemical ingredients for life travel between stellar systems. We wish to understand the role of ISOs in the spread and evolution of organic matter in the universe. Telescopic observations show that organic compounds exist in the protoplanetary disks of other stellar systems (e.g. Carr & Najita, 2008; Öberg et al., 2015) and are a significant component of the interstellar medium (ISM) (Tielens 2008). Thus, ISOs may contain a significant quantity of organic material. The presence of ISOs within the Solar System implies that the Solar System is an open system that exchanges matter with nearby extrasolar systems. The amount of mass transfer may be substantial, with some models predicting that up to 90% of the Oort cloud may be comprised of captured ISOs (e.g. Levison et al., 2010). However, whether ISOs can be vectors of pre-biological material is unknown. While the harsh radiation environment of interstellar space may severely alter surface properties of ISOs (Jewitt, 2017; Fitzsimmons et al., 2018), if complex organic-like molecules can survive within an ISO on the long journey through space, prebiotic chemistry may be exchanged between solar systems. Demonstrating that ISOs could transfer or enrich pre-biotic compounds from system to system would change the current understanding of where life can arise within the galaxy.

2.2 Bridge science objectives

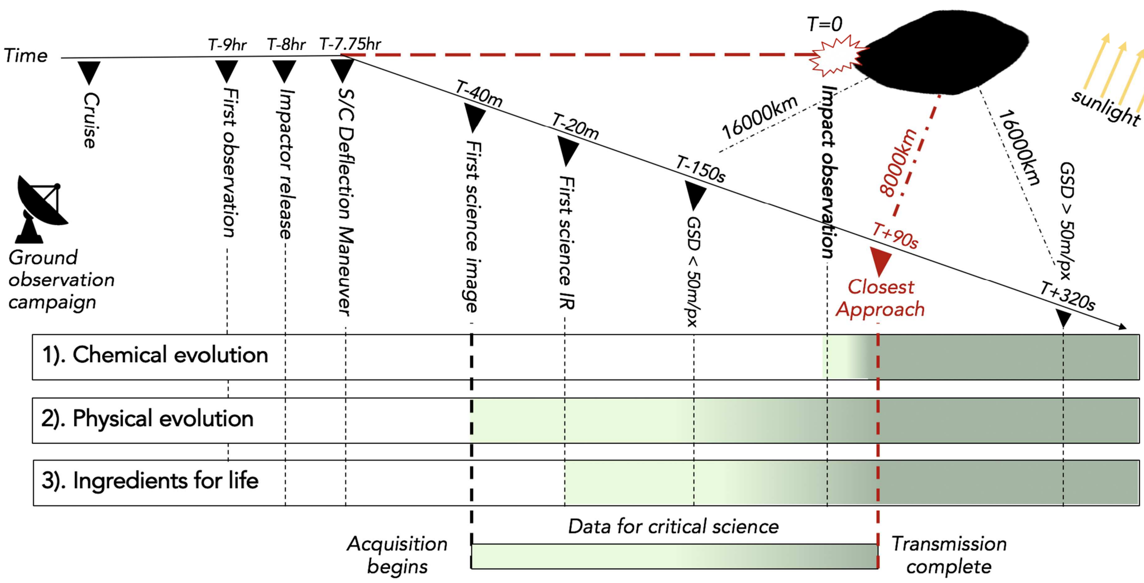
To address our science goals, we outline three key science objectives for a mission to an ISO. We propose Brid



ge such that it conforms to hypothesis driven investigation as required for NASA's New Frontiers AOs. However, proposing a mission to an as-yet-undiscovered ISO is a new and unique challenge because the object's type/class and origin would be unknown. The target ISO could fit any one of the previously mentioned ISO origin hypotheses, making it difficult to propose testable hypotheses for an ISO. Thus, we focus on science objectives that address questions applicable for any type of ISO, and we highlight the exploratory nature of visiting an ISO for the first time.

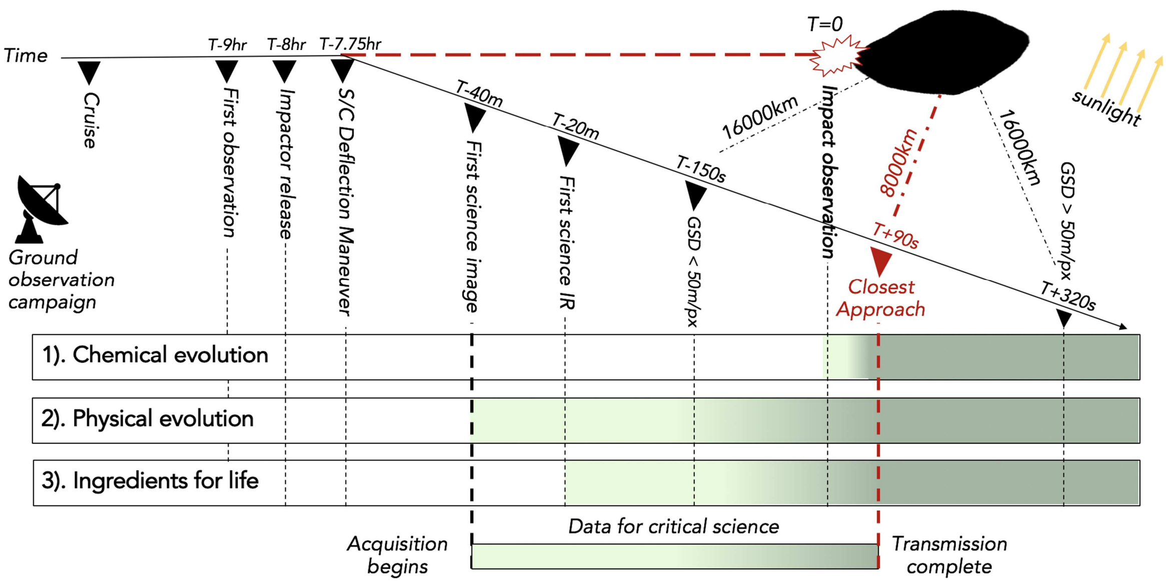
2.2.1 Science Objective 1

Determine whether the ISO formed in an environment with chemical composition similar to the Solar System. The chemical composition of an ISO determines the environment in which it formed and could possibly help identify a specific system of origin. Knowing the system of origin would provide context for understanding the formation of the ISO itself and its broader implications for solar system formation. Efforts have shown trajectory modeling can be used to identify possible candidates for the home systems of interstellar objects, such as Carina or Columba in the local Orion Arm for 1I/'Oumuamua (Hallat & Wiegert, 2020). Definitively reducing this list to a single system of origin though is likely impossible using trajectory data alone, due to the significant uncertainty in star positions and velocities and potential for multiple scattering events (Zul



uaga et al., 2018; Dybczynski et al., 2018; Zhang, 2018; Bailer-Jones et al., 2019; ‘Oumuamua ISSI Team et al., 2019). However, the chemistry of the ISO, particularly the isotopic ratios and abundances of volatiles may provide additional constraints on the ISO’s possible system of origin, and the chemical differences between stellar systems more broadly. If an ISO is from a star from a class different from our own sun, we would expect it to exhibit different elemental abundances, expressed, for example in different relative abundances of volatile elements (e.g., Bodewits et al. 2020 for I2/Borisov).

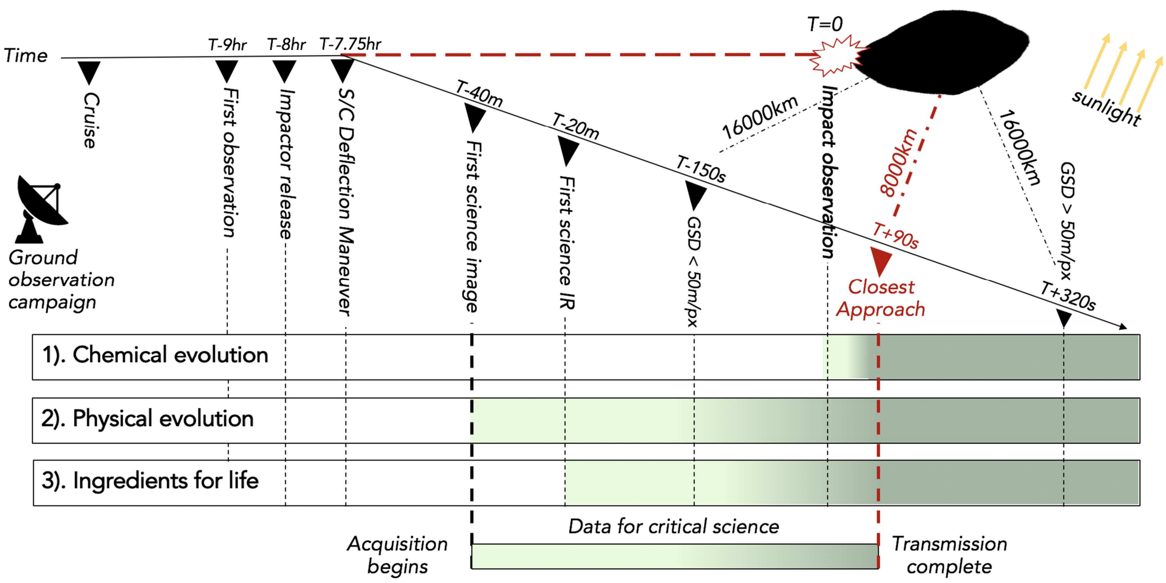
The meteoritics community already uses isotopic composition measurements of pre-solar grains (stardust) to determine their extraterrestrial sources for and to study the chemical evolution of galaxies and stellar atmospheres (Davis 2011, Zinner 2014). The isotopic signature of an object has been found to be strongly connected to that of its host star(s). For example, in our solar system, □^{16}O and □^{17}O values for various objects including chondrules, the Earth, Moon, and Mars all fall along a tight fractionation line that begins at the □^{16}O/□^{17}O value of the Sun (McKeegan et al. 2011). In contrast, the isotopic variations exhibited by pre-solar grains are at least four orders of magnitude greater than those of terrestrial and solar system objects. Accordingly, systems such as $^{14}N/^{15}N$, $^{12}C/^{13}C$, $^{29}Si/^{30}Si$, $^{16}O/^{18}O$ and $^{17}O/^{18}O$ are used as diagnostics to link these grains to specific sources such as red giant stars, carbon stars, and supernovae, as well as to understand mixing within the solar nebula (Zinner 2014). The relative abundances of noble gas



es (e.g., argon, krypton) and their isotopic composition are also indicative of the composition of the gas cloud in which the ISO's star system originated (Verchovsky & Sephton 2005, Wieler 2002).

Measuring the aforementioned isotopic ratios and noble gases in an interstellar object would indicate the class of stellar system that the ISO originated from. Comparing elemental abundance and isotope ratio measurements with those observed in the solar wind (McKeegan et al. 2011), Solar System objects (e.g. Clayton et al. 1993, Kobayashi et al. 2003, Liu et al. 2009), other star systems (e.g. Harris & Lambert 1984, Smith et al. 2009), pre-solar grains (Zinner et al., 2014), and nebulae (e.g. Yurimoto & Kuramoto 2004) could possibly determine the parent star of the ISO's system. This, combined with orbital considerations might help narrow down on a possible source region, even if the answer would likely be non-unique. Although information on the composition of specific exoplanetary systems is limited (e.g., isotope information is mostly missing), in situ ISO exploration offers an opportunity to investigate in detail the chemical variation across these systems. In cases where it is possible to obtain independent dynamical constraints on the origin region for the ISO, we can use it as a probe of the composition of that region.

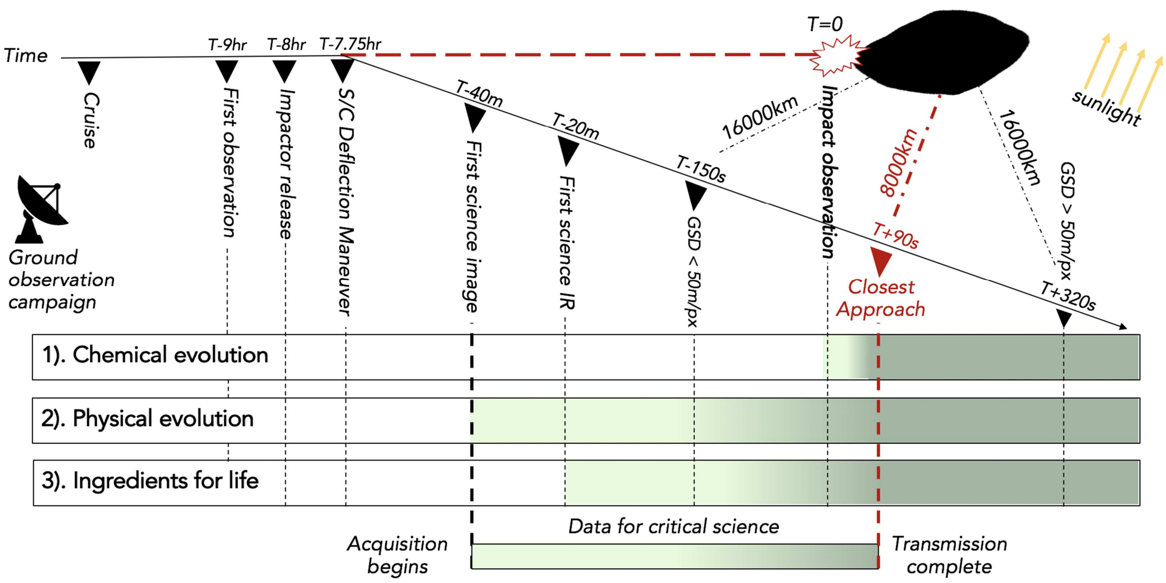
2.2.2 Science Objective 2



Determine whether the ISO physically resembles known classes of objects in the Solar System. The flux of detectable interstellar objects is likely dominated by small (<10 km) bodies (Trilling et al., 2017; Do et al., 2018). The Solar System contains many types of objects in this size category, each with distinct chemical and physical characteristics (Asphaug, 2009). Some are relatively pristine rocky and icy bodies, such as primitive asteroids and comets from the asteroid belt, Kuiper Belt, Oort Cloud, and other dynamical groups. Others are evolved rocky or metallic bodies, such as 16 Psyche, which are thought to be the core of differentiated bodies exposed by impacts (Asphaug et al., 2006). By comparing the ISO's geologic composition, structure, and geomorphology (such as the presence of craters) to known classes of objects in the Solar System, we can check whether the ISO's host system has/had a formation environment (e.g. formation temperature and level of collisional activity) that is similar to the Solar System.

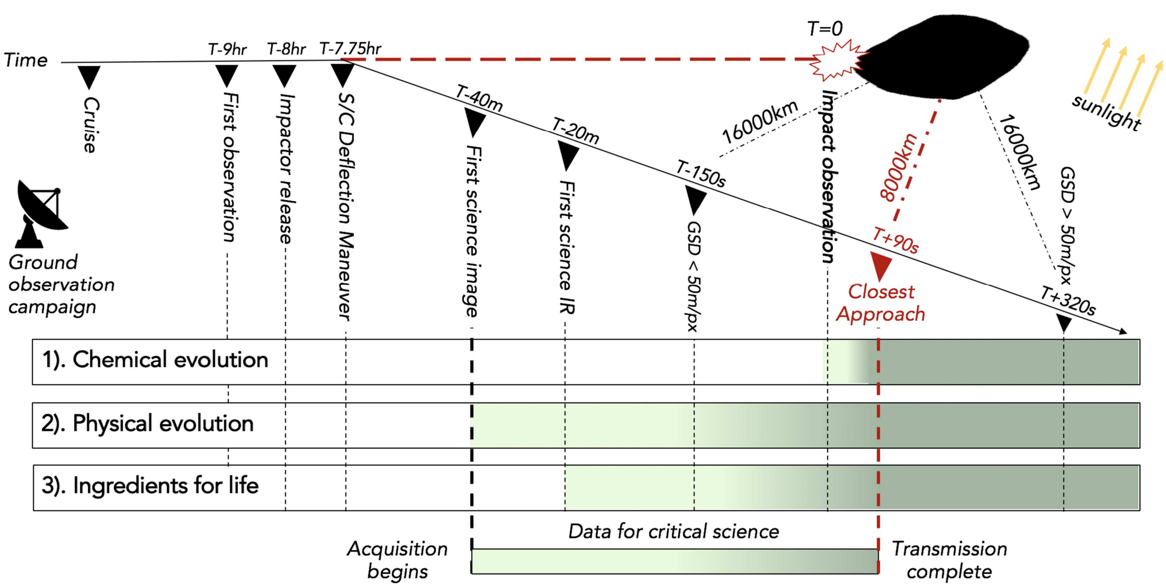
2.2.3 Science Objective 3

Determine whether the ISO contains prebiotic ingredients. In the Solar System, potential prebiotic ingredients such as amino acids, CHNOPS particles, polycyclic aromatic Hydrocarbons (PAHs), or nitrogen-containing organics exist in small bodies such as Comet Wild 2 (Mumma and Charnley, 2011; Meierhenrich et al., 2014), 1P/Halley (Huebner and Boice, 1992), 67P/Churyumov–Gerasimenko (Meierhenrich et al., 2014; Capaccioni et al., 2015; Goesmann et al., 201



5; Wright et al., 2015), and interplanetary dust particles (Clemett et al., 1993). More specifically, acetonitrile (CH_3CN) and propionitrile (CH_3CH_2CN) were identified in recovered Stardust samples (Glavin, Dworkin & Sandford 2008), and ethylene glycol ($HOCH_2CH_2OH$) was detected in comet C/1995 O1 Hale-Bopp (Hudson and Moore, 2000; Corviser et al., 2004). These complex organics suggest that early Solar System chemical processes foster the formation of significant quantities of prebiotic material. Likewise, determining if prebiotic ingredients are present within an ISO can indicate whether the necessary chemistry for life as we know it is present in another stellar system and can be transferred from one stellar system to another.

Spectroscopic measurements of 1I/'Oumuamua revealed a flat, reddish spectrum which could indicate an organic-rich surface exposed to cosmic rays (Fitzsimmons et al., 2017). However, the spectrum could also be consistent with a non-organic, iron-rich surface ('Oumuamua ISSI Team, 2019). While some observations of C2 and CN in 2I/Borisov suggest it is comparable to some of the most carbon-depleted comets in our solar system (Fitzsimmons et al., 2019; Opitom et al., 2019; Lin et al., 2020), more recent reports that examine the time history 2I/Borisov's cometary activity suggest it may only be barely depleted (Bannister et al., 2020). Thus, the presence or absence of organic compounds in either object is uncertain. Bridge would search for signatures from PAHs, tholins, and various types of chemical bonds relevant to prebiotic chemistry. These measurements would be used to compare the ISO with prebiotic signals from small bodies in our own solar system.



2.3 Relevance to

decadal survey

The unique opportunity afforded by an interstellar object drives the two overarching science goals of the Bridge mission concept, which address Priority Questions (PQs) identified by the Planetary Science Decadal Survey (NRC, 2011). Table 1 summarizes Bridge's science goals and objectives with their connections to PQs; a complete science traceability matrix can be found in Appendix A.

Science Goal A addresses PQs 1, 2, 3, and 10. PQ 1 asks, *"What were the initial stages, conditions, and processes of solar system formation and the nature of the interstellar matter that was incorporated?"* The chemical and mineralogical components of an ISO carry information about the raw ingredients representative of its home stellar system. Studying these components can shed light on the similarities and differences in solar system formation processes between systems.

PQ 2 asks, *"How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?"* There are several models for how planets formed and migrated in our solar system (e.g. Tsiganis et al., 2005; Walsh et al., 2011; Öberg & Wordsworth, 2019) that each predict the ejection of distinct types of material into interstellar space. Thus, the composition and physical structure of an interstellar object would shed light on the type of material ejected from its home stellar system and the processes leading to its ejection. This would provide important context for understanding the migration of giant planets in our own solar system.

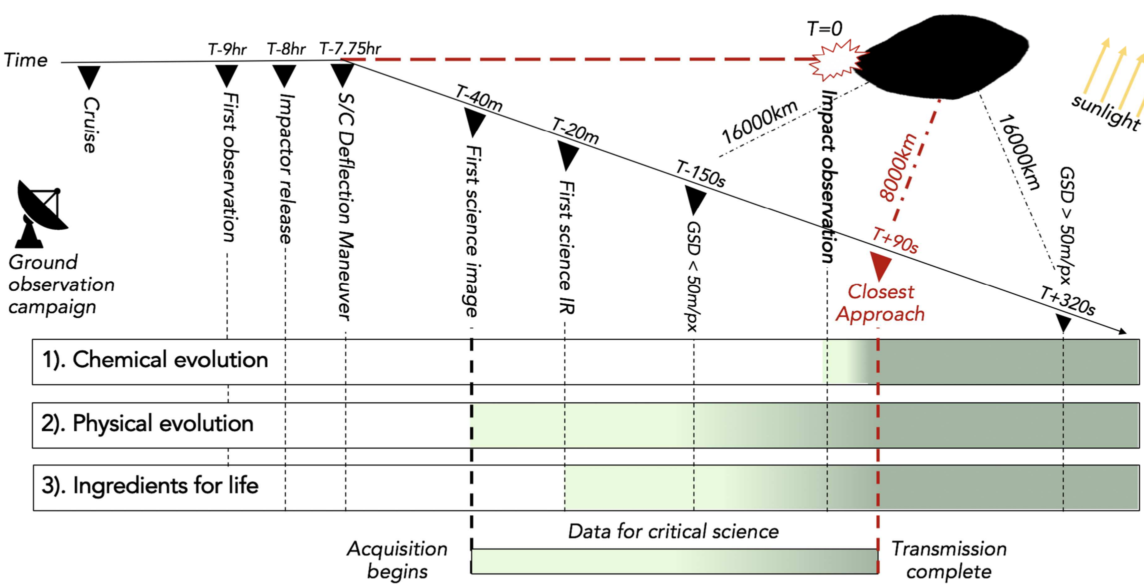
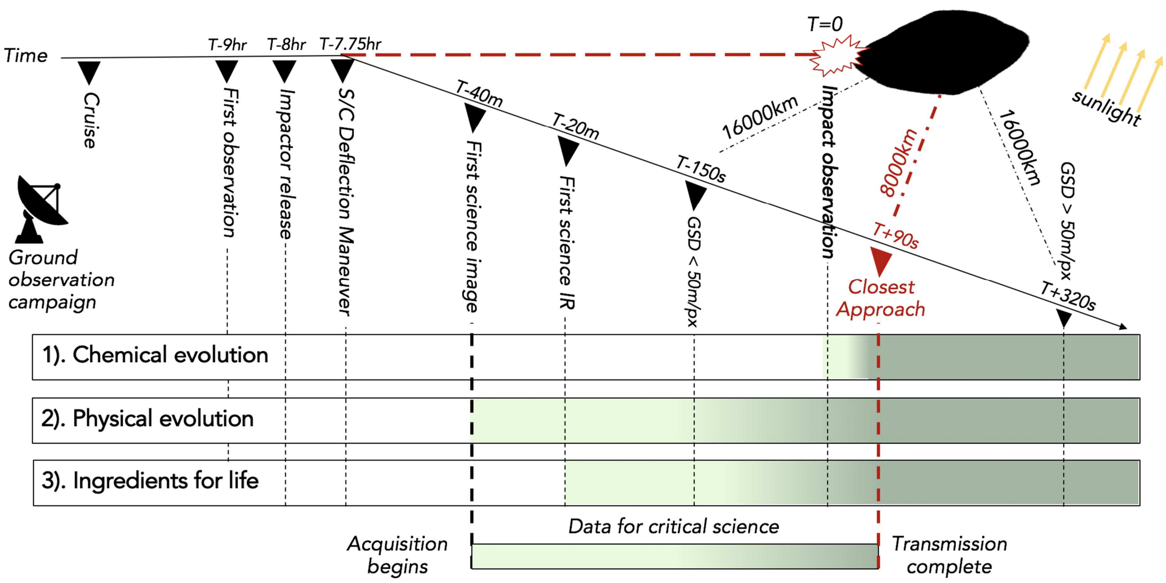
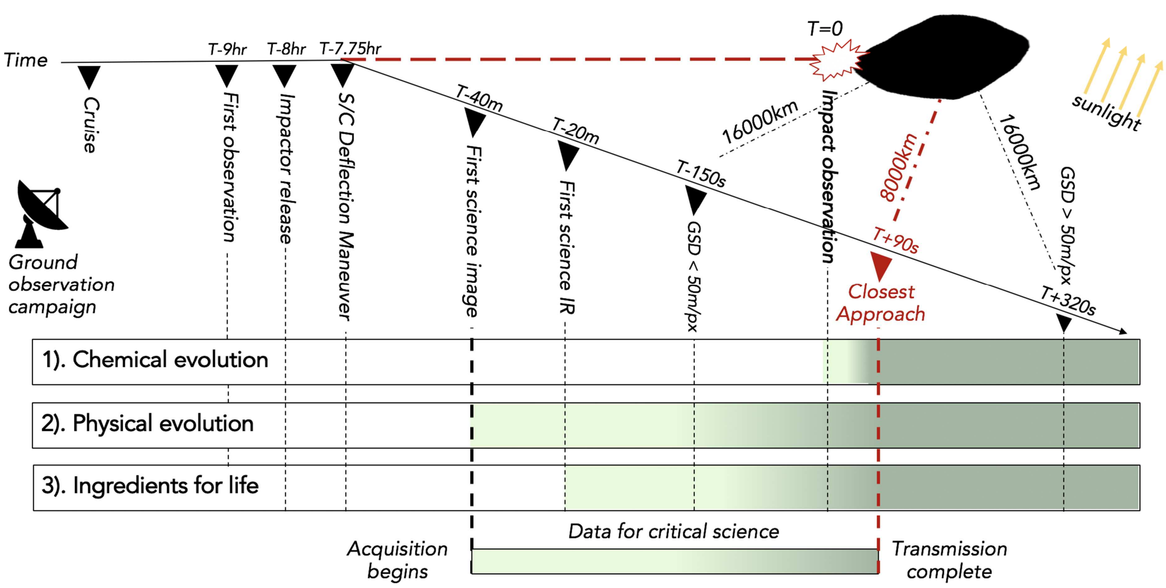


Table 1: Relevance of science objectives to decadal survey science goals & priority questions.

Decadal Priority Questions Addressed (NRC, 2011)	*Science Goal*	*Science Objective*	*Physical Parameters*
***PQ1**. What were the initial stages, conditions and*	*A). Determine whether the*	*1). Determine whether the ISO*	*The ratio of $\delta^{18}O/^{16}O$, $\delta^{17}O/^{16}O$*

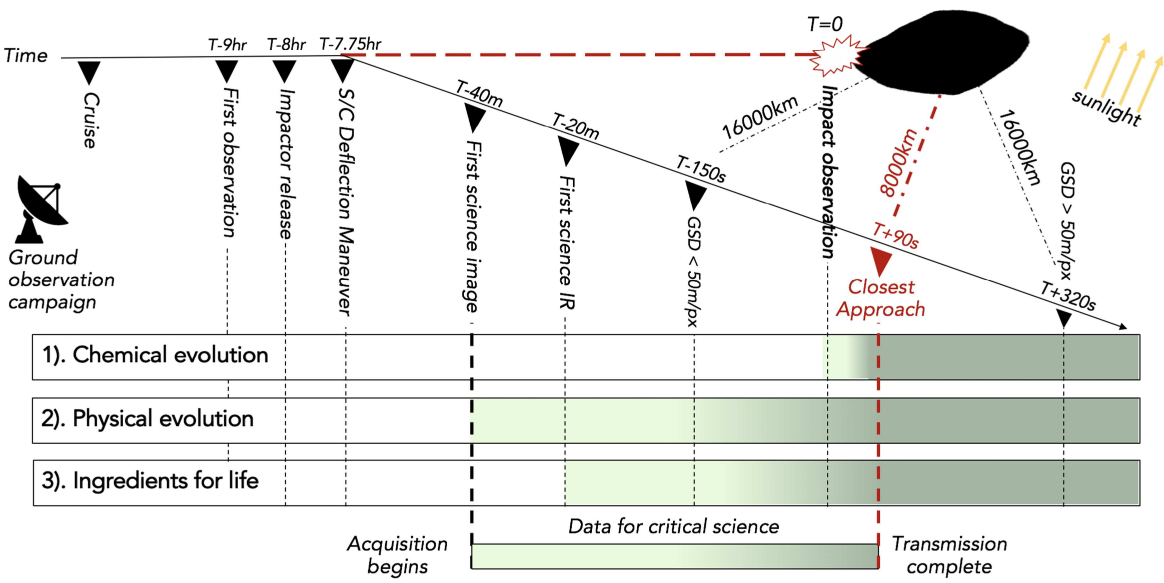


processes of solar system formation and the nature of the interstellar matter that was incorporated? ***PQ2.*** *How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?* ***PQ3.*** *What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?* ***PQ10.*** *How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?*	*Solar System evolved like other stellar systems within the Milky Way galaxy.*	*formed in an environment with chemical composition similar to the Solar System.*	*Atomic abundances*
			Relative abundances of noble gases
		2). Determine whether the ISO physically resembles known classes of objects in the Solar System.	*Spectral identification of rocks and ices*
			The molar abundances of minerals
			Bulk morphological properties of the ISO
Q4. *What were the primordial sources of organic matter, and where does organic synthesis continue today?*	*B). Determine whether the basic chemical ingredients for life travel between stellar systems.*	*3). Determine whether the ISO contains prebiotic ingredients.*	*The presence of functional groups of organic matter. PAHs and tholins are particularly interesting for their biologic and space weathering implications.*
			The presence of OH, CH, and N2



			The abundance of N, P, and S relative to O

PQ 3 asks, *"What governed the accretion, supply of water, chemistry, and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play?"* Similarly, PQ 10 asks, *"How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?"* While interstellar objects by definition originate from outside our solar system, they can provide important insights into these questions through the lens of comparative planetology. Just as observations of exoplanets challenged our notions about the formation and migration of planets in our own system, so too might observations of exoplanetary building blocks such as interstellar objects influence our understanding of planetary accretion processes. An interstellar object's physical and chemical characteristics elucidates the processes by which it formed and evolved, and whether these processes are similar to those inferred for the formation of classes of bodies in our own solar system. More directly, interstellar objects represent a significant source of incoming projectiles through our own solar system whose properties are still poorly understood. In addition to contributing to the evolution of the solar system through direct bombardment, captured ISOs may also represent a significant fraction of the objects in our Oort Cloud (Levison et al., 2010). The ability to observe an interstellar object at close range would also provide insight into the

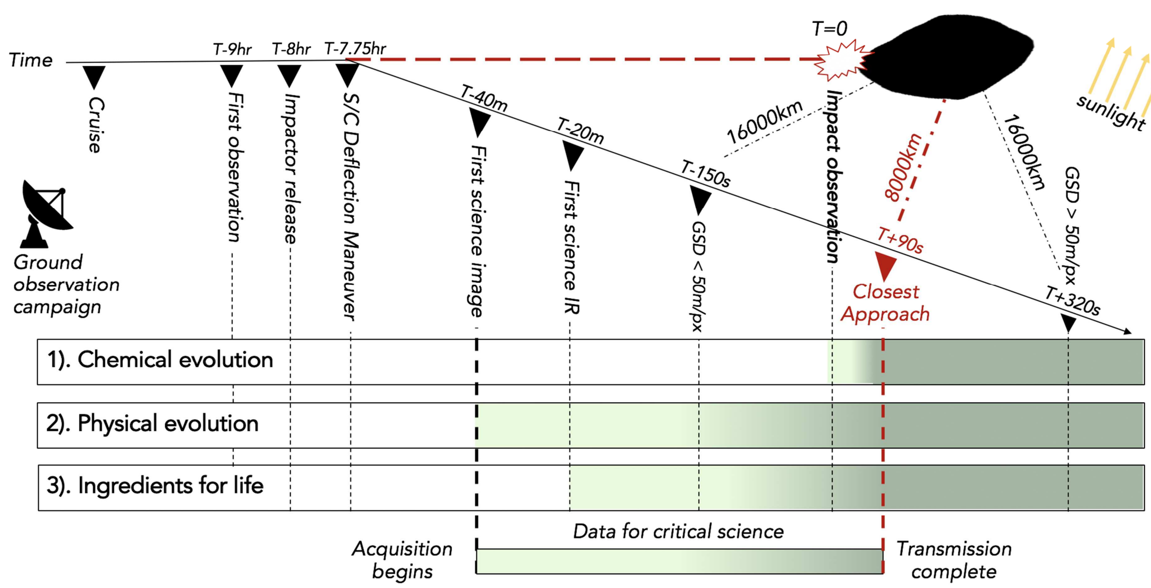


Astronomy and Astrophysics Decadal Survey's (NRC, 2010) Science Frontier Question, *"How diverse are planetary systems?"*

Science Goal B addresses PQ 4, which asks, *"What were the primordial sources of organic matter, and where does organic synthesis continue today?"* Investigating the organic components of an interstellar object would provide insight into whether the basic ingredients for life can survive the journey through interstellar space and answer if ISOs are a source of organic matter for the Solar System. This is also relevant to the Science Frontier Question, *"Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?"* from the Astronomy and Astrophysics Decadal Survey (NRC, 2010).

3. Science implementation

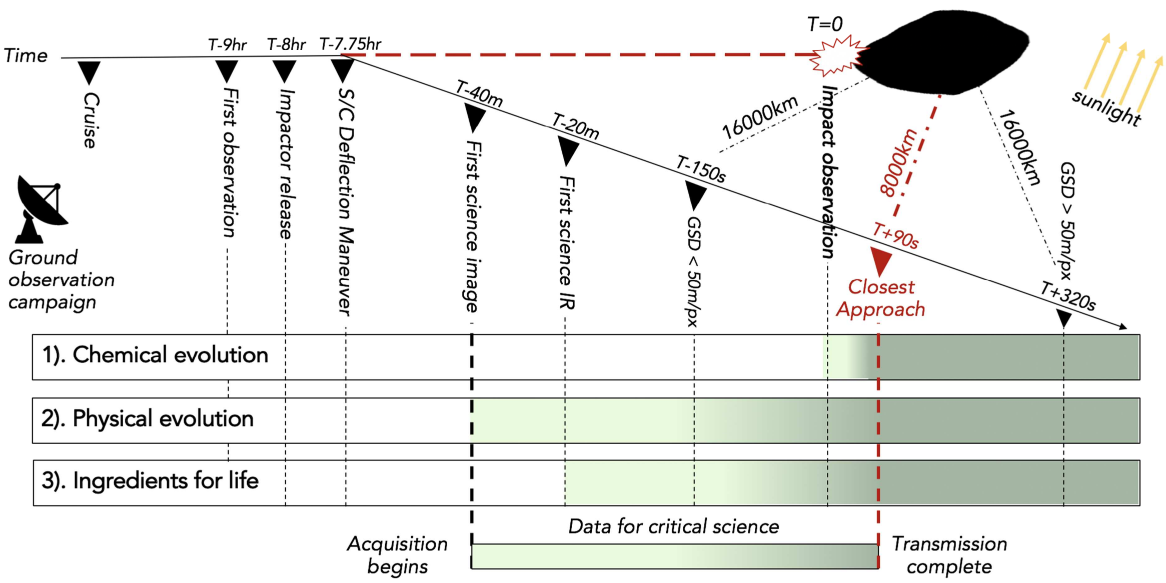
Bridge's instrument payload would address the aforementioned science goals and objectives regardless of the specific properties of the target ISO. We outline a remote sensing payload suite consisting of a mid-infrared spectrometer, a near infrared spectrometer, an ultraviolet/visible spectrometer, and a visible light camera. In addition to the remote sensing suite, an impactor would expose the ISO's interior material, allowing observation of fresh ISO material in case the ISO's surface has experienced extensive space weathering during its journey through the ISM. An impactor could also enable volatile characterization by inducing outgassing. All instruments in Bridge's payload are based on previously flown instruments. Figure 1 illustrates all the



spectral features we wish to observe, motivating our instrument selection. For more details on our methodology for instrument selection, including a detailed discussion on the rationale for our decision to not include a mass spectrometer, see Section 6.1.1 Instrument Trades.

3.1 Visible Camera

Taking images of geological features on the ISO's surface during the flyby addresses science objective 2. Bridge would use a camera design based on the Long Range Reconnaissance Imager (LORRI) aboard the New Horizons spacecraft (Cheng et al., 2009) and the High Resolution Imager (HRI) aboard the Deep Impact spacecraft (Hampton et al., 2005). The camera would measure wavelengths spanning 0.35-0.85 μm. Given the light conditions available between 0.7 AU to 2 AU, the camera would be capable of reaching a signal-to-noise ratio (SNR) of > 440 with an exposure time of 100 ms and assuming the ISO has an albedo comparable to typical comet nucleus (0.04; Lamy et al., 2004). The camera would have an aperture and focal length of 30 centimeters and 10.5 meters, respectively, producing a field-of-view of 2 mrad and a resolution of 20 m per pixel during closest approach of the ISO. This is a slight adjustment from LORRI's aperture and focal length specifications. A filter wheel would also be included as part of the telescope and would feature red, green, blue filters for color imaging; and a blackout filter (e.g. Hampton et al., 2005) to prevent detector saturation during impact.



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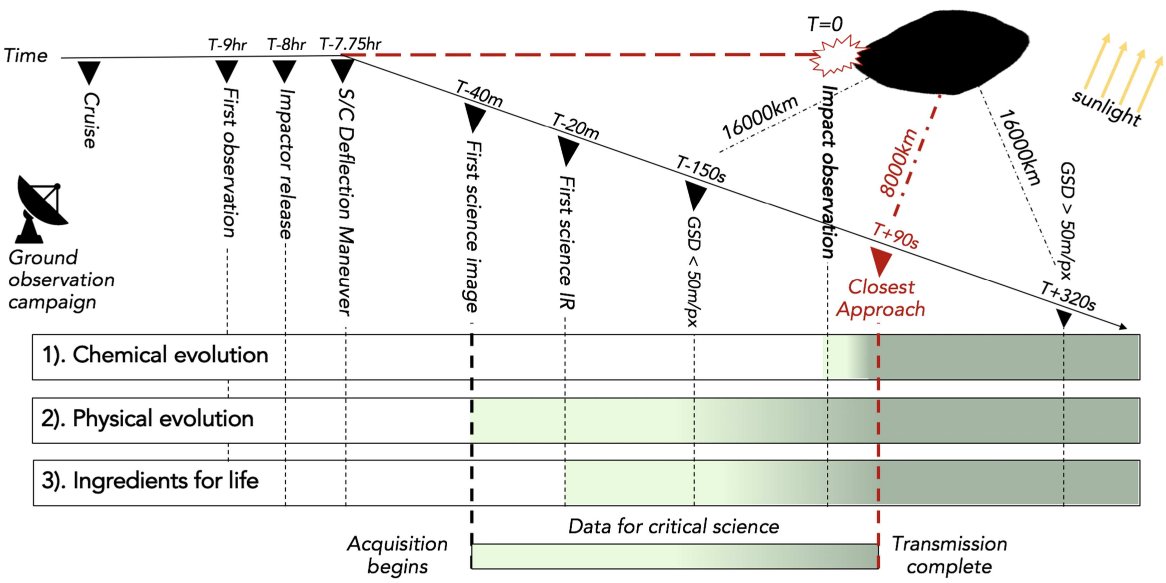
phase, a high frame rate of 20 Hz would allow the camera to rapidly capture images as the plume evolves. LORRI was designed for a readout time of 0.25 second, thus our imager would need to be modified to increase the frame rate. The Deep Impact mission was able to accomplish readout times as low as 0.06 s by using image sub-framing. If the ISO and impact do not take up the full-frame of pixels, a sub-frame of the image can be read out to reduce the frame rate (Hampton et al., 2005).

3.2 Near-Infrared Point Spectrometer

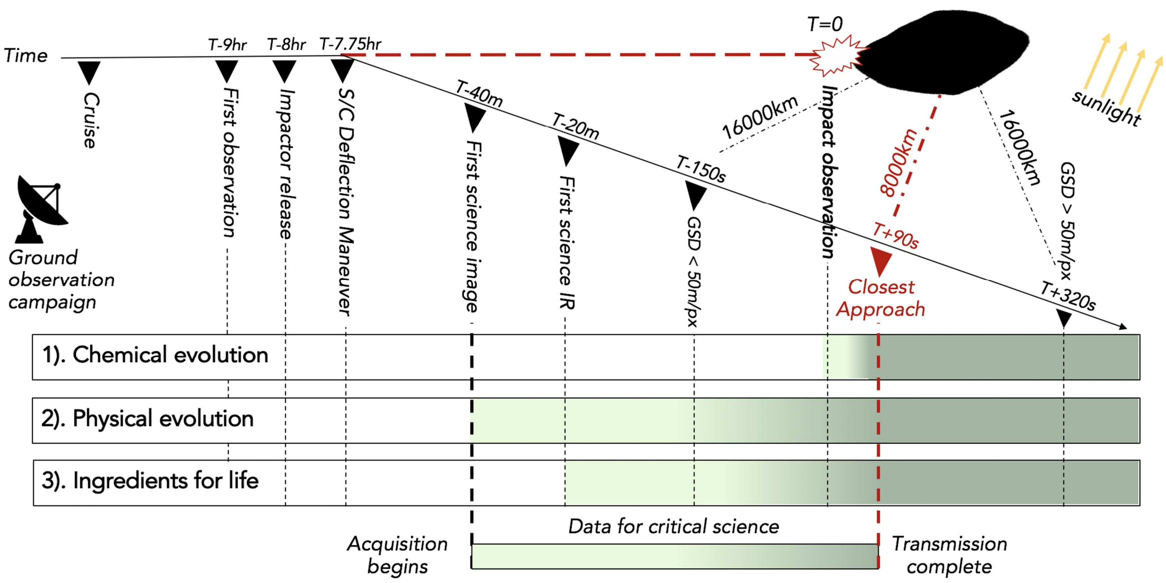
Near-infrared (NIR) spectrometers are frequently employed in exploratory missions to small bodies with unknown surface compositions due to their ability to measure a wide range of chemical compounds. Bridge's NIR point-spectrometer would be based on the design of OSIRIS-REx's OVIRS spectrometer (Reuter et al., 2018). An adjusted aperture of 8 cm and a focal length of 35 cm would offer Bridge's NIR spectrometer a 4-mrad diameter circular field of view (FOV). We choose a wavelength sampling range of 1-4 μm and a spectral resolution of 10 nm for the instrument so that it could resolve relevant prebiotic molecular components (objective 3) such as N_2 (2.15 μm), C-H (3.2-3.4 μm) and O-H bonds (1.6-2.5 μm, 2.7-2.8 μm) on the surface of the ISO and within the impactor plume. Additionally, we are interested in resolving rock forming minerals and ices (objective 2) such as plagioclase (1-1.5 μm), olivine (1 μm), pyroxene (2 μm), CO_2 ice (1.4, 1.6, 2.0, 2.7 μm), H_2O ice (1.05, 1.3, 1.55, 1.65, 2.0, and 3.1 μm), NH_3 ice (2.0, 2.1, 3.0



μm), CH_4 ice (1.0, 1.65, 1.82, 2.2 μm), and N_2 ice (2.15 μm). Bridge's NIR, like OVIRS, is a point spectrometer, meaning the full spectrum of an area on the target surface corresponding to the FOV is obtained in a single frame. See Figure 1 for more details on the potential spectroscopic features that Bridge would observe.

3.3 Mid-Infrared Point Spectrometer

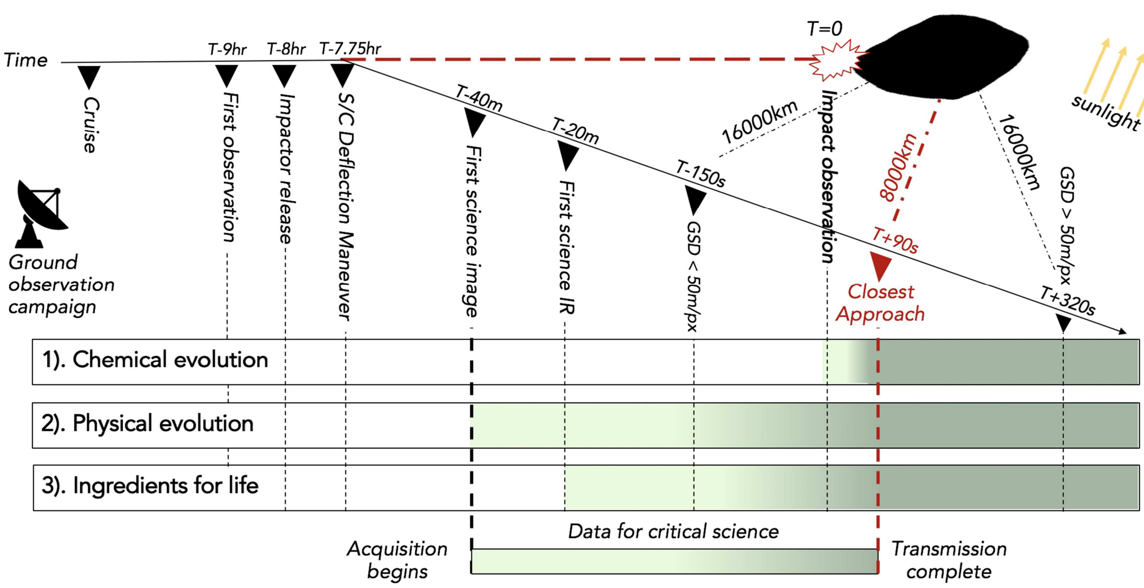
Bridge's science objective 2 requires measuring the abundances of rock forming minerals such as plagioclase (9.7-10.6 μm), olivine (9.5-12 μm), oxides (13.1 μm), and clinopyroxenes (9-9.8 and 10-12 μm; e.g. Christensen et al., 2018; Stenzel et al., 2017; Zolensky et al., 2006; Hanner and Zolensky, 2010). Similarly, Bridge's science objective 3 requires identifying key organic functional groups and species relevant to prebiotic chemistry, such as aliphatic (7.4 μm) and unsaturated hydrocarbons (12.5), PAHs (7-14 μm), oxygen groups (7.4 μm), nitrogen groups (6.5 μm), ketones and carbonyls (7.14 μm), and tholins (5.3 μm); see Figure 1 for more details on the potential spectroscopic features that Bridge would observe. The corresponding spectral signatures to address both objectives lie within the mid-infrared (mid-IR) and can thus be obtained with a point spectrometer similar to OTES, the mid-IR point spectrometer aboard OSIRIS-REx (Christensen et al., 2018), but with a detector designed to sample a smaller wavelength range at higher resolution. Bridge's mid-IR spectrometer would combine the optics box from OTES with a commercially available sensor prod uce d by Oce an Insi



ght to create an instrument capable of measuring spectra from 5-15 µm with a spectral resolution of 0.01 µm, measuring absorptions as small as 0.75%. We select these spectral characteristics according to what is necessary to resolve the spectral lines relevant to science objective 2 and 3. The mid-IR instrument would take reflectance spectra of the surface before and after closest approach and would take emission spectra of the plume immediately following the impactor collision. A high maximum frame rate of 20 Hz upon impact is desired in order to capture the rapid thermal evolution of the plume. The mid-IR spectrometer would thus provide spectra of both the surface and the interior of the object, as well as the ejecta material.

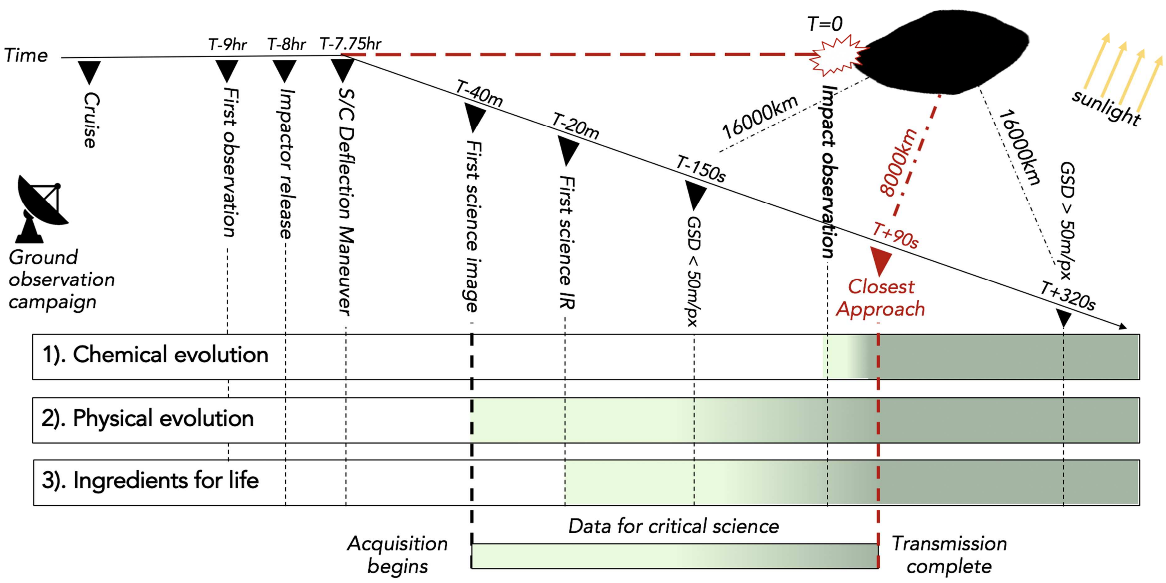
3.4 Ultraviolet/Visible Point Spectrometer

Bridge would carry an ultraviolet/visible (UV-VIS) spectrometer to investigate the ISO's chemical and isotopic composition. This spectral regime can be used to determine atomic and noble gas abundances (Almandos and Raineri, 2007) and isotopic ratios such as $\delta^{16}O/\delta^{18}O$ (Hutsemékers et al., 2008) relevant for objective 1. These measurements would also address objective 3 by constraining elements pertaining to prebiotic chemistry such as N, O, P and S (Robert et al., 2016; McClintock et al., 2015). During the inbound and outbound phases of the critical flyby sequence, the UV-VIS instrument would perform long exposure (Figure 2) reflectance observations of the surf



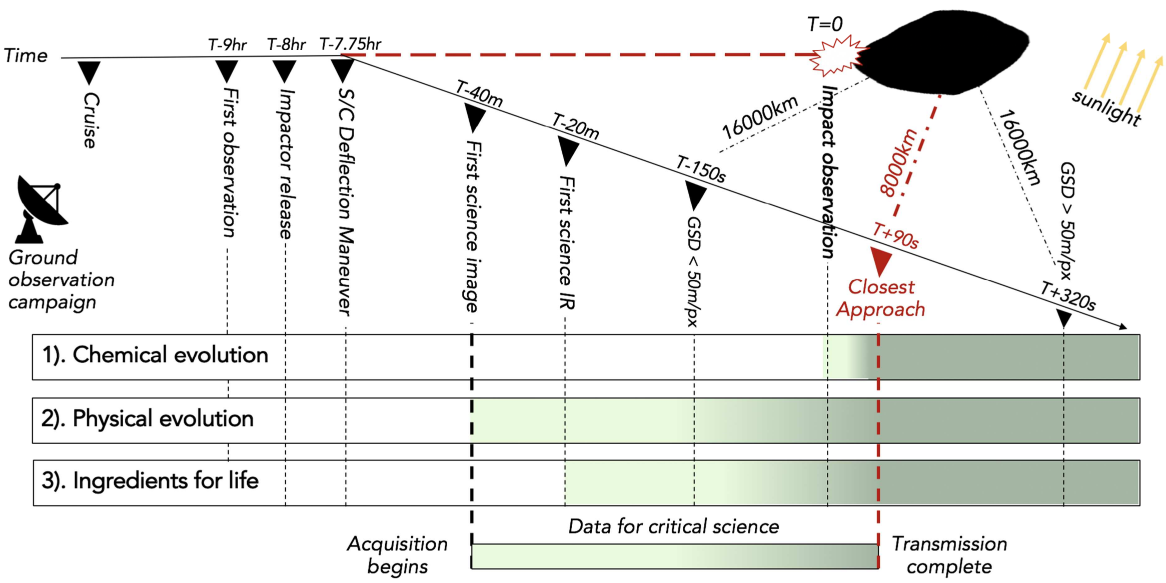
ace and of any naturally occurring coma, if present. Following the impact event, the instrument would collect compositional data of the interior by acquiring emission spectra from ejected plume material at a sampling rate of 20 Hz, which would ensure the acquisition of spectra at a variety of plume temperatures. We will be able to detect NOPS absorption lines in any measurement that we perform. CHNOPS and noble gases emit lines at <10000 K and we should be able to detect them immediately following the impact event.

To meet these observational requirements, we choose a UV-VIS instrument point spectrometer with heritage from MAVEN's IUVS (McClintock et al., 2015), UVIS-NOMAD on TGO (Robert et al., 2016), and New Horizons' ALICE (Stern et al., 2009). The instrument concept features a linear array of 1000 channels sampling the 200-600 nm spectrum at 0.4 nm resolution, and a 20 cm aperture. The spectral range and resolution were chosen to detect the spectral lines of noble gases (i.e., Ne at 540 and 585 nm, Ar at 459 and 473 nm, Kr at 557 nm, and Xe at 481 and 492 nm), prebiotic elements (i.e., N at 400 nm, P at 254 nm, S at 420 nm, O at 278 nm), and other elemental abundances (i.e. K at 208 nm, Al at 264 and 282 nm, Ni at 299 nm, Fe at 238 and 375 nm, Na at 314 and 589 nm, Ti at 336 and 521 nm, Ca at 393 and 397, Mn at 403 nm, Mg at 518 nm, and Si at 567 nm). Additionally, the instrument would include an echelle channel with 0.009 nm resolution spanning 305-320 nm to distinguish oxygen isotopic ratios sufficient to resolve the 0.03 separation between the ^{16}OH and ^{18}OH lines at the (1, 1) 312.1 nm band (Hutsemékers et al., 2008). A 20 cm aperture would ensure sufficient light flux in low albe do and low



illumination environments. See Figure 1 for more details on the potential spectroscopic features that Bridge would observe.

Under normal conditions, a UV-VIS spectrometer requires long integration times (on the order of several seconds to a minute), consequently requiring the instrument to integrate throughout the inbound approach. However, since we are only interested in making bulk measurements of the ISO, point spectrometry is sufficient and thus long integration times are not challenging, which may not be true of imaging spectrometers. This logic dictates our decision to use point spectrometers over imaging spectrometers (see Section 6.1.1 for more details). The inclusion of reaction wheels as part of the spacecraft's mechanical design (see Section 5.2.4) would ensure the instrument is adequately pointed at the ISO throughout its integration time. Once the impactor plume has been generated, the necessary integration time would be significantly shorter (on the order of 10's of milliseconds) due to the increase in photon availability. With short integration times, rapid data procurement of the evolving plume during the impact-to-closest approach phase of the flyby would be achievable.



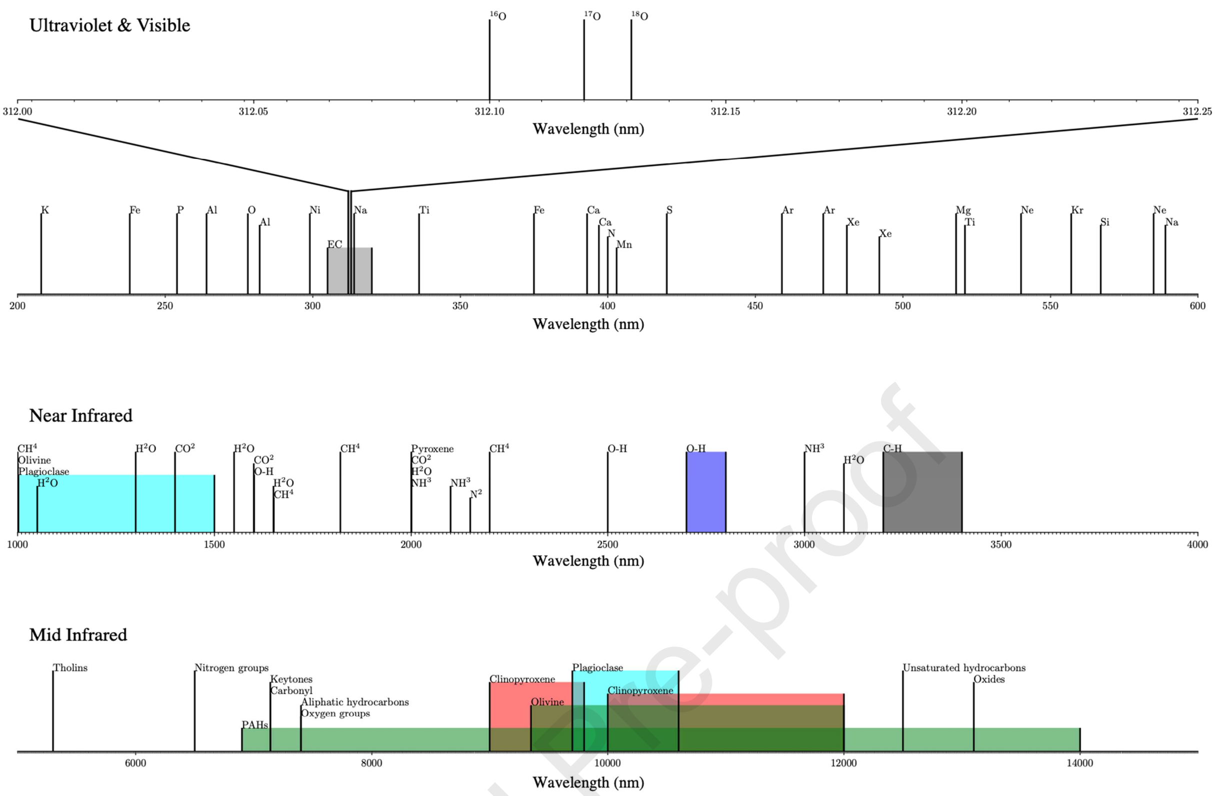
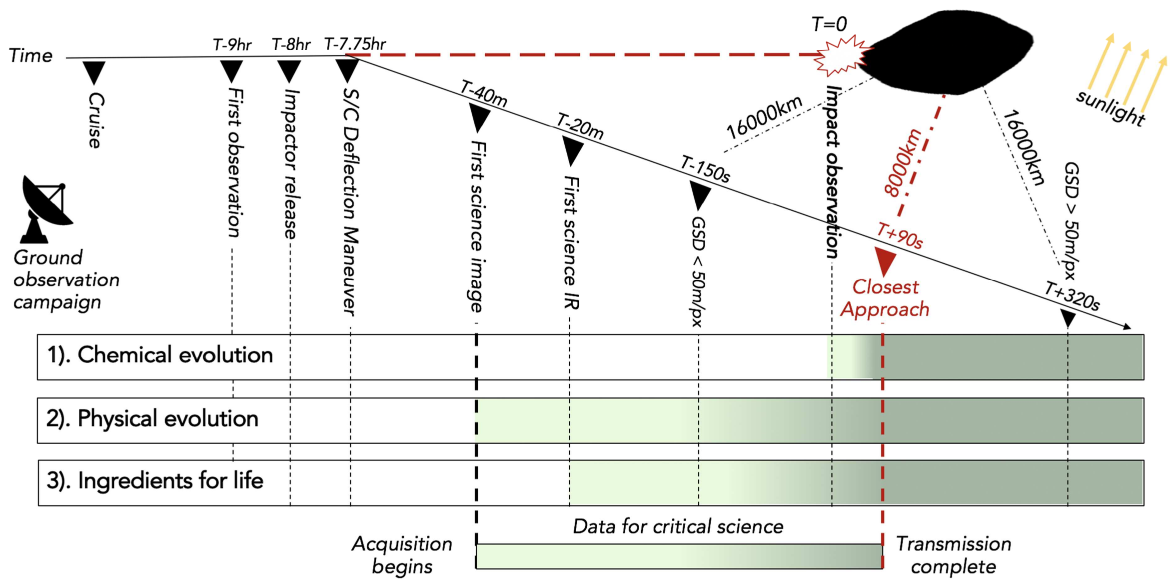


Figure 1. The spectral features that Bridge's spectrometers are designed to observe. The top plot corresponds to the spectral range of the UV-VIS spectrometer, and includes the Echelle Channel (EC) that is designed to differentiate between the oxygen isotopes. The middle plot corresponds to the spectral range of the near-IR spectrometer, where features that are characterized by trends over a range of wavelengths are depicted as shaded boxes. Finally, the bottom plot corresponds to the spectral range of the mid-IR spectrometer. On all plots, the minor ticks represent the resolutio



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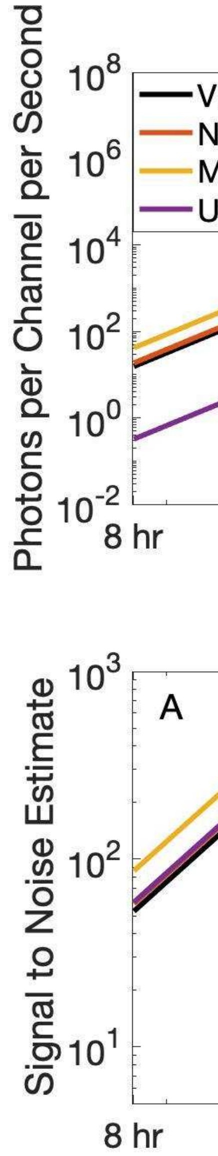


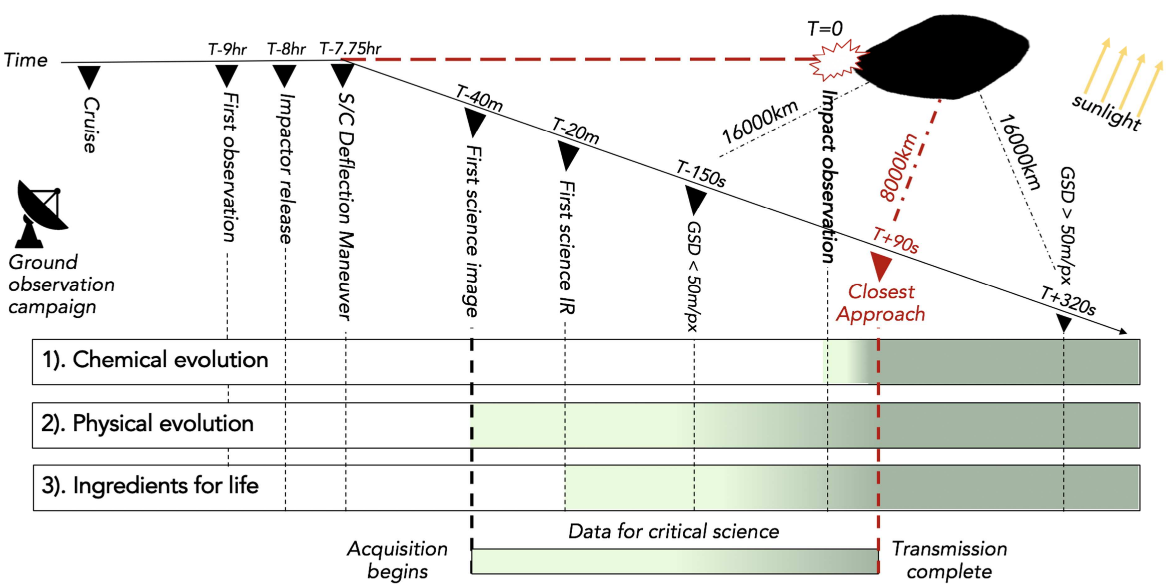
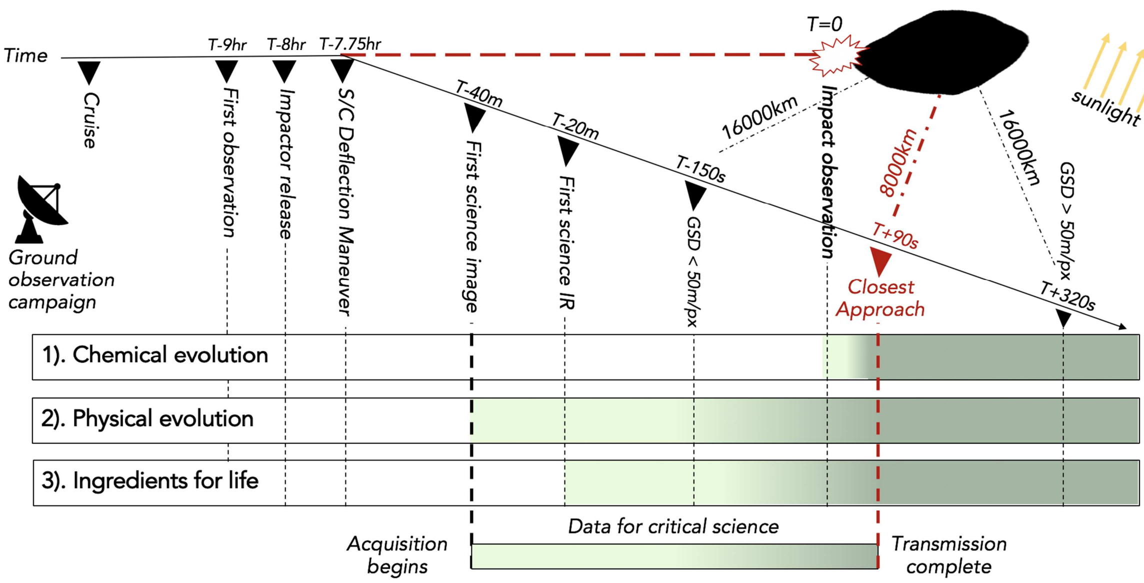


Figure 2. *Top:*

Estimated photon flux for the instruments as Bridge approaches the ISO. *Bottom:* Estimated signal to noise ratio (SNR) for the instruments as Bridge approaches the ISO. Upon approach, the necessary exposure time to optimize SNR would reduce, allowing for shorter integration times. We estimate the SNR for three different integration times during three phases of the ISO flyby: A, B, and C, which are labelled accordingly on the plot. Phase A starts at 8 hours before impact and proceeds to 1.5 hours before impact. The visible camera, near-IR and mid-IR have integration times of 1 hour during this phase. Phase B goes from 1.5 hours to 10 minutes before impact. Integration times here are 1 minute for the visible camera, Infrared instruments, and 1 hour for the UV-VIS. Phase C is just before impact. The visible camera and IR instruments have integration times of 1 second, the UV-VIS has an integration time of 1 min. We assume that the ISO is an 1I/'Oumuamua sized object and has an albedo of 0.04 (neglecting emissivity), and that the spacecraft encounters the object at 1 AU on a 70 km/s flyby. We calculate noise via the method discussed in McClintock et al. (2015).

3.5 Impactor

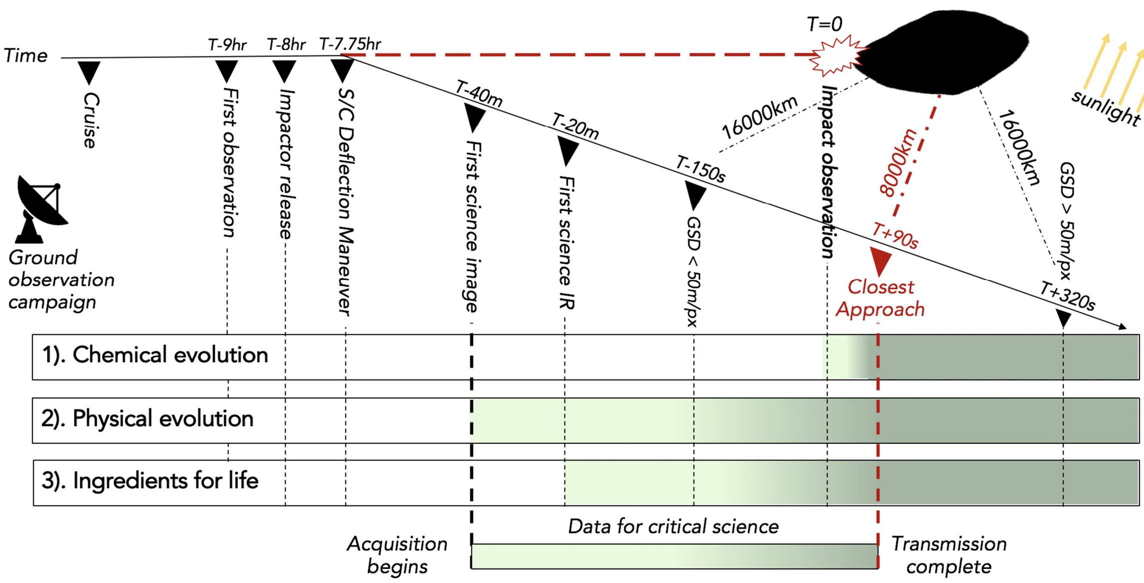
An impactor is necessary to excavate material from the ISO's interior. While science objectives 1 & 2 could be partially answered with observations of the ISO's surface, material from the ISO's interior that has not experienced space weathering would give a more accurate picture of the object's hist



ory in its original host system. Additionally, the ISO’s surface may have experienced significant space weathering such that extensive devolatilization (i.e., outgassing) from prolonged exposure to the interstellar medium and intense bombardment by galactic cosmic rays occurred during its voyage through interstellar space (Seligman & Laughlin, 2018; Vavilov & Medvedev, 2019), obscuring the ISO’s original composition and necessitating an analysis of interior material to achieve science objective 3. For example, the Deep Impact (DI) mission detected polycyclic aromatic hydrocarbons on Comet Tempel 1 only following impact (A’Hearn et al., 2005). This was also likely due to the greatly enhanced signal-to-noise ratio achieved during impact (e.g. Sunshine et al., 2007).

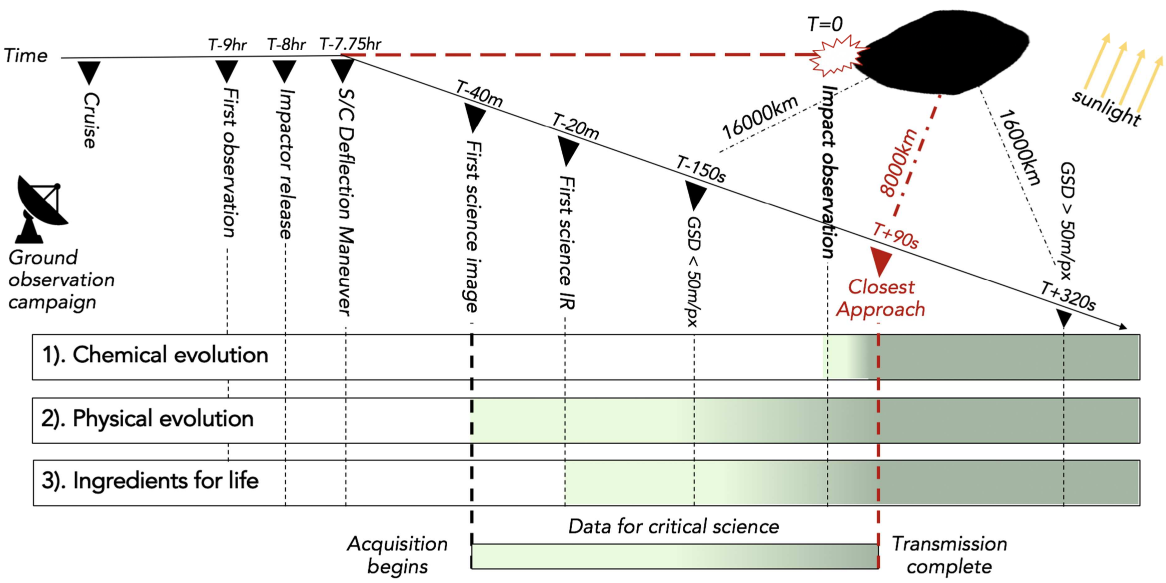
Upon impact, the impactor would vaporize part of the ISO material and generate a plasma flash that would allow the spectrometers to observe spectral emission lines. The intense emission of photons due to the high-energy kinetic impact would also increase the signal-to-noise ratio for all of the spectroscopic instruments aboard the Bridge spacecraft. This would greatly enhance the quality of the observations made for objectives 2 and 3. A UV spectrometer (Section 3.5) would observe the plasma flash and constrain the atomic abundances and isotopic ratios of the target, and is a necessity for completing the observations for science objective 1. The plasma flash would also improve measurements made from space- and ground-based telescopes, as was demonstrated during the Deep Impact mission (Lisse et al., 2006).

The Bridge impactor would also include an onboard camera similar to that of Deep Impact’s Impactor Targ



eting Sensor (ITS) (Hampton 2005). The camera's primary purpose is to facilitate image-based autonomous guidance (i.e., AutoNav) to guide the impactor into a collision-course with the ISO. However, images from the camera could also address science objective 2. As it nears impact, the impactor camera's images of the ISO's surface would have a resolution of 10 m/pixel. This is higher resolution than the main spacecraft's camera, because the impactor camera would travel closer to the ISO's surface than the main spacecraft and have less motion distortion (since no slewing would be necessary to keep the ISO in view on a collision course). The impactor would also be capable of smart detection, increasing the number of images that could be sent back to the main spacecraft despite the high encounter velocity. The higher resolution of the impactor images would enable more detailed analysis of surface morphologies at small scales and provide context to the spectral data from Bridge's spectrometers (Section 3.3-3.5).

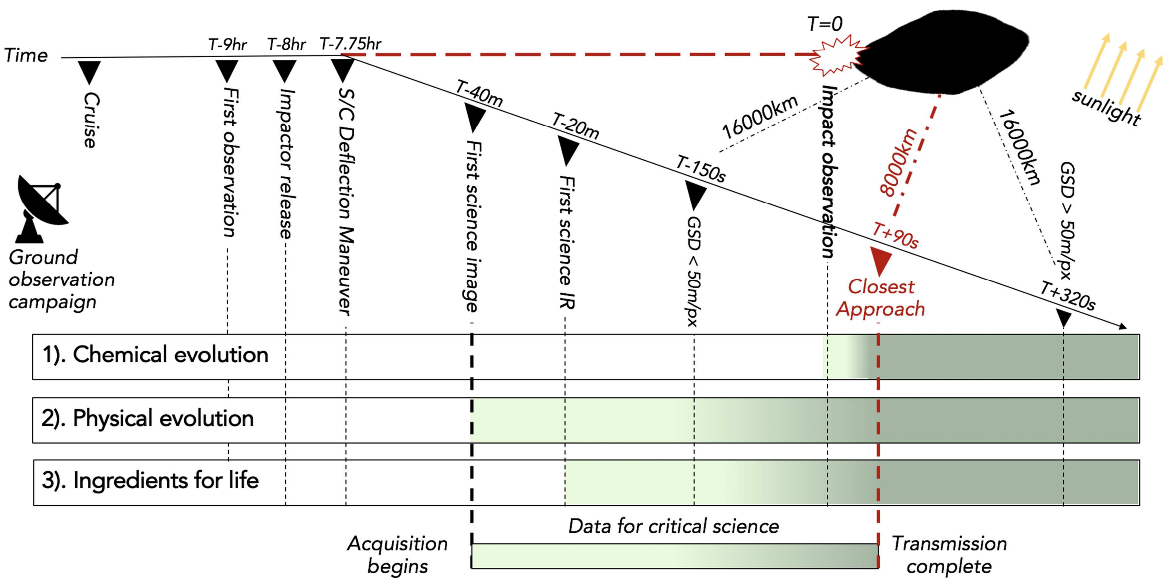
The design of Bridge's impactor follows the mission heritage of DI, which released an impactor on Comet Tempel 1 (A'Hearn et al., 2005). The DI impactor was 350kg in total: 250kg of base spacecraft mass, and an additional 100kg of copper weight. For our study, we consider the heritage impactor as a black box spacecraft with no alterations except for the removal of the extra 100kg of copper weight. Since the relative velocities for Bridge's encounter would likely be much higher than they were for Deep Impact, a simple energy scaling (½ mv^2) suggests that a smaller mass impactor would be sufficient to achieve the same impact energy. If the systems within a Deep Impact style impactor could be sufficiently reduced in mass, a CubeSat-class spacecraft (~5-10 kg)



would potentially be sufficient for our listed science objectives. However, designing a new autonomous impactor would require another complete feasibility study and is beyond the scope of this mission design, but could be explored further in future studies.

Table 2: Bridge spectroscopic instrument list

Instrument	Aperture	Focal Length	FOV	Mass	Spectral Range	Resolution (Spatial or Spectral)	Heritage Peak Power	Size of detector or pixel size
Visible Camera	30 cm	10.5 m	2 mrad	25 kg	350 nm - 850 nm	20 m/pixel	15 W	1024x1024
Near-IR	8 cm	350 mm	4 mrad	17.7 kg	1 - 4 μm	10 nm	10 W	18x18 μm
Mid-IR	15 cm	66 cm	4 mrad	23 kg	5 - 15 μm	10 nm	15 W	20x20 μm

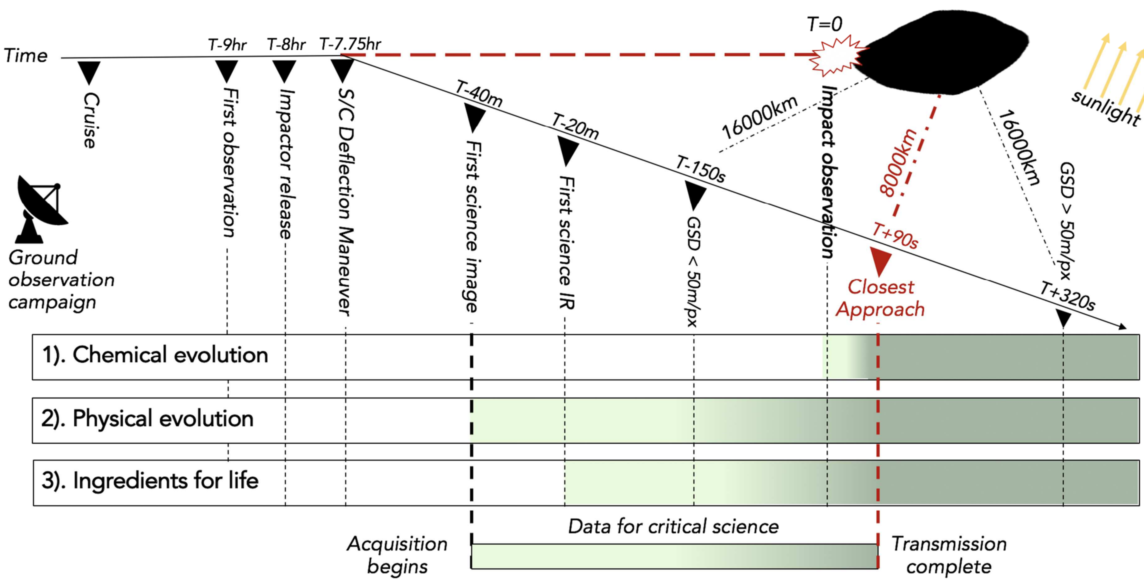


UV-VIS	20 cm	43 cm	1 mrad	25 kg	200 - 600 nm	0.4 nm	10 W	35 mm
Impactor Camera	12 cm	2.1 m	10 mrad	12 kg	300 - 1100 nm	10 m/pixel	18 W	1024x1024

4. Mission design:

4.1. Target selection: Unique challenges in studying ISOs

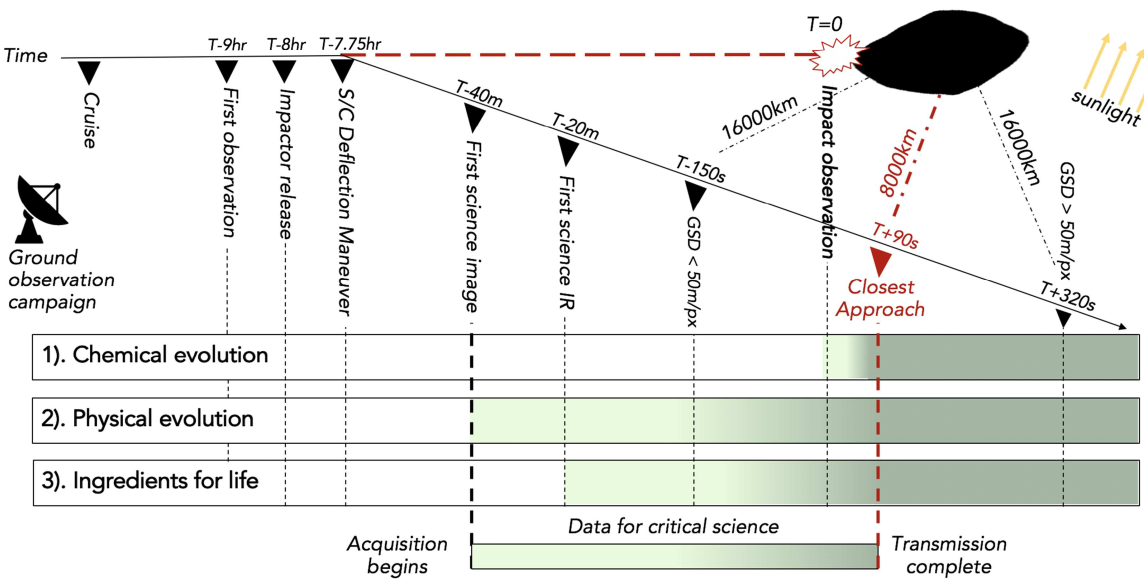
There are three main categories of mission architectures for visiting an ISO: 1) flyby/intercept missions that may have high relative velocities between the spacecraft and the ISO, 2) rendezvous missions where the spacecraft matches the position and velocity of the object, and 3) landing/sample return missions where either the spacecraft rendezvouses with the object and lands on the object's surface softly. Each of these mission architectures potentially yields a higher



science return but also requires a higher level of complexity and cost to accomplish. Due to the high complexity and cost of an ISO rendezvous, we propose a flyby/intercept mission architecture for Bridge. Other studies of mission architectures to comets (e.g. ESA's AMBITION, Bockelée-Morvan et al., 2019) have also noted the difficulty of a rendezvous and landed mission due to the surface gravity and activity of the object. The inclusion of an impactor significantly improves Bridge's science return without the cost and complexity increase of rendezvousing with the ISO. Additionally, the inclusion of an impactor on the payload allows for enhanced compositional analysis, which would prove difficult for other mission types like a surface landing or sample return due to the rapid approach speeds of interstellar objects.

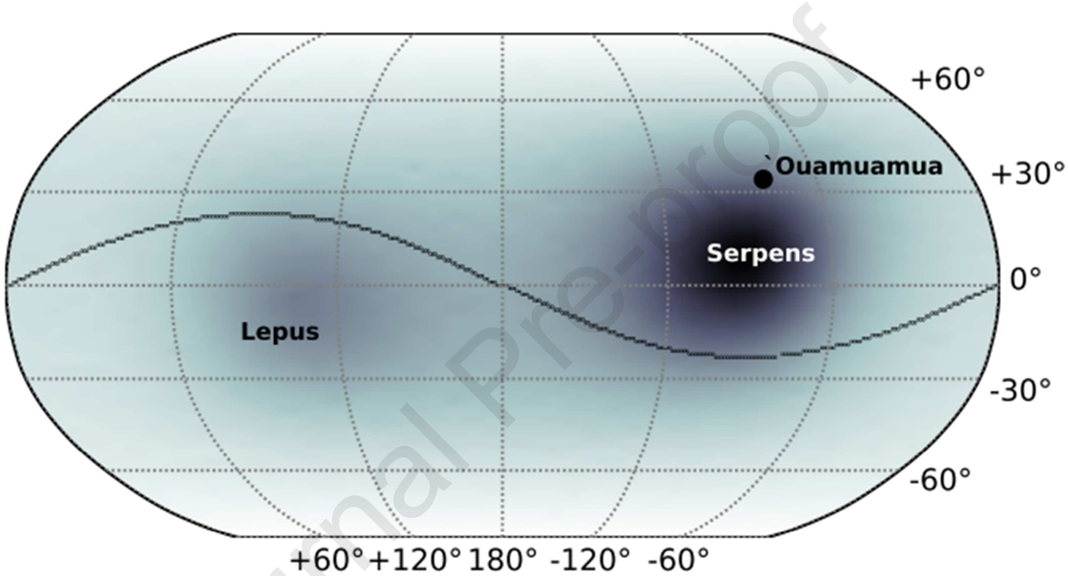
4.1.1 ISO Trajectories

Interstellar objects that pass through our solar system are not gravitationally bound to the Sun, meaning they fly by our sun on a hyperbolic path. The duration and shape of the flyby trajectory is determined by the closest approach to the Sun (i.e., perihelion) and the velocity of the ISO at an infinite distance away from the Sun (i.e., hyperbolic excess velocity). The higher an ISO's perihelion or hyperbolic excess velocity, the less its trajectory is influenced by the Sun's gravitational acceleration and the higher its eccentricity. Thus, a fast ISO with perihelion in the outer solar system follows a nearly straight line and has an eccentricity approaching infinity. Meanwhile, a slower ISO with a perihelion in the inner solar system has a more parabolic trajectory with

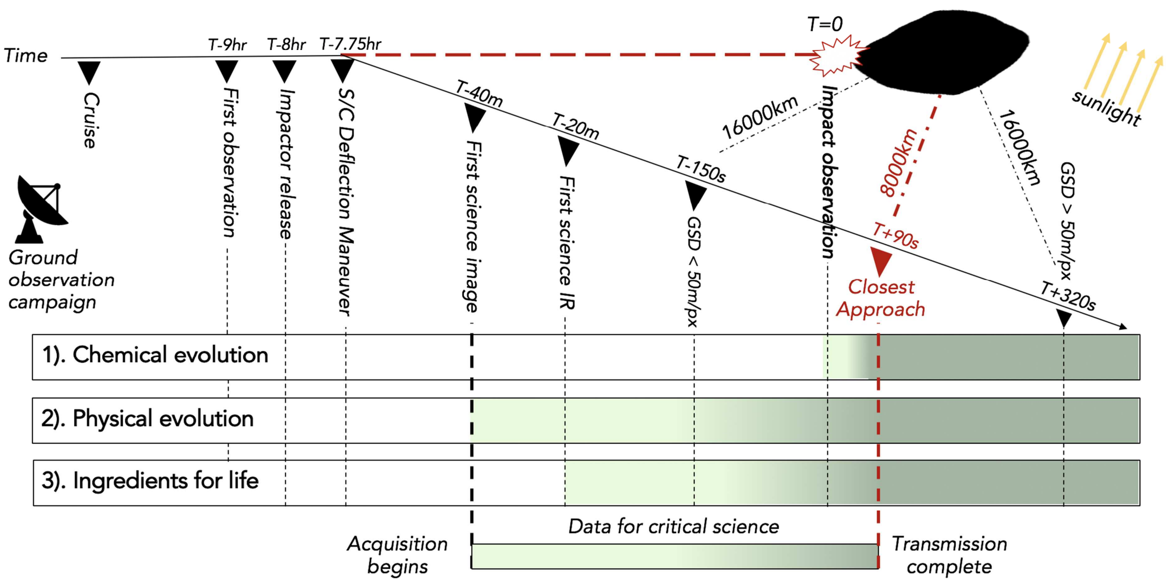


an eccentricity approaching one (Engelhardt et al., 2017). Since the perihelion and eccentricity of the next ISO could be anything within a wide range of values, Bridge must be able to accommodate a wide range of potential mission trajectories — including trajectories perpendicular to the ecliptic.

Figure 3. A probability sky map, representing the probability of an interstellar object



approaching on a trajectory parallel to the vector pointing from the sun to that area of the sky. Axis labels are degrees from a heliocentric perspective. Darker colors represent a higher probability of an interstellar object approaching our solar system from that direction. Reproduced from Seligman

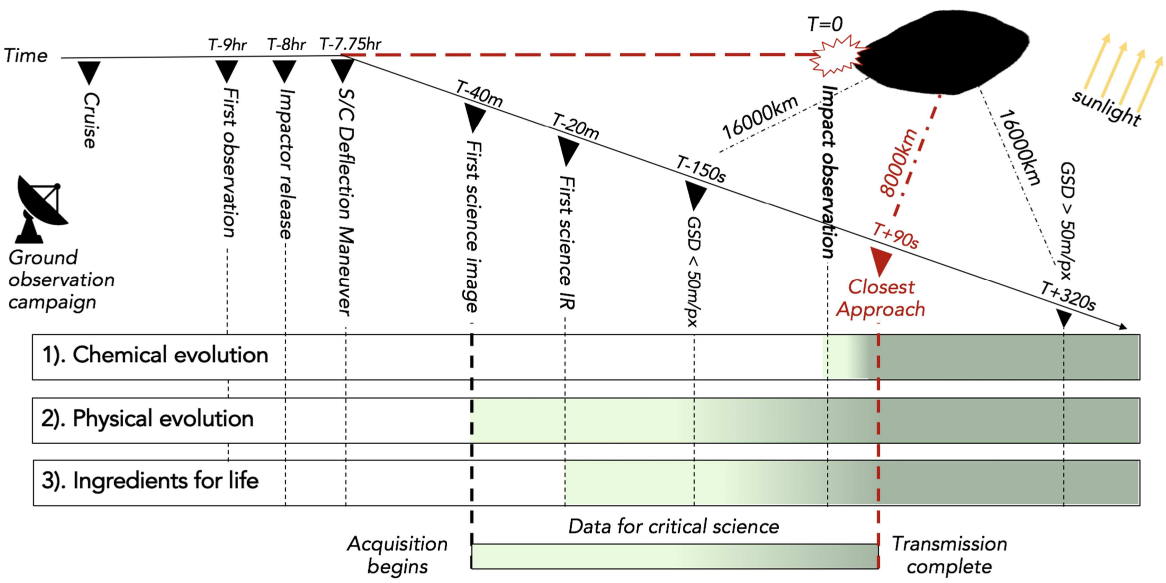


and Laughlin 2018 by permission of AAS.

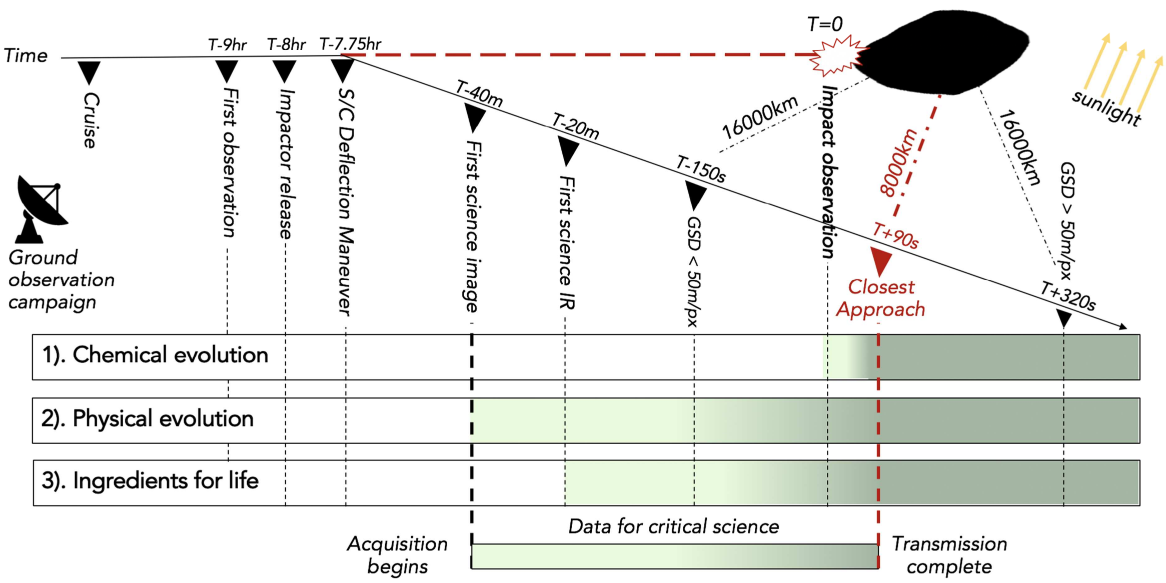
We broadly separate potential ISO encounters into two possible encounter regions: those that pass within the inner Solar System (inside the orbit of Mars), and those that travel mainly through the outer Solar System (outside the orbit of Mars). Inner Solar System intercepts are feasible when the ISO's ascending or descending node on the ecliptic plane falls within the inner solar system. Thus, if a spacecraft is on an inner Solar System intercept trajectory, it would launch from Earth to encounter the target near its perihelion in the inner solar system. Meanwhile, an outer solar system intercept could reach an ISO outside the solar plane by relying on gravity assists to achieve high inclination change. However, this approach depends on the alignment of the ISO's trajectory with the other planets in the solar system. We have designed Bridge to use an inner solar system ISO intercept trajectory; the trade between an inner and outer solar system intercepts justifying this decision is discussed in Section 6.1.2.

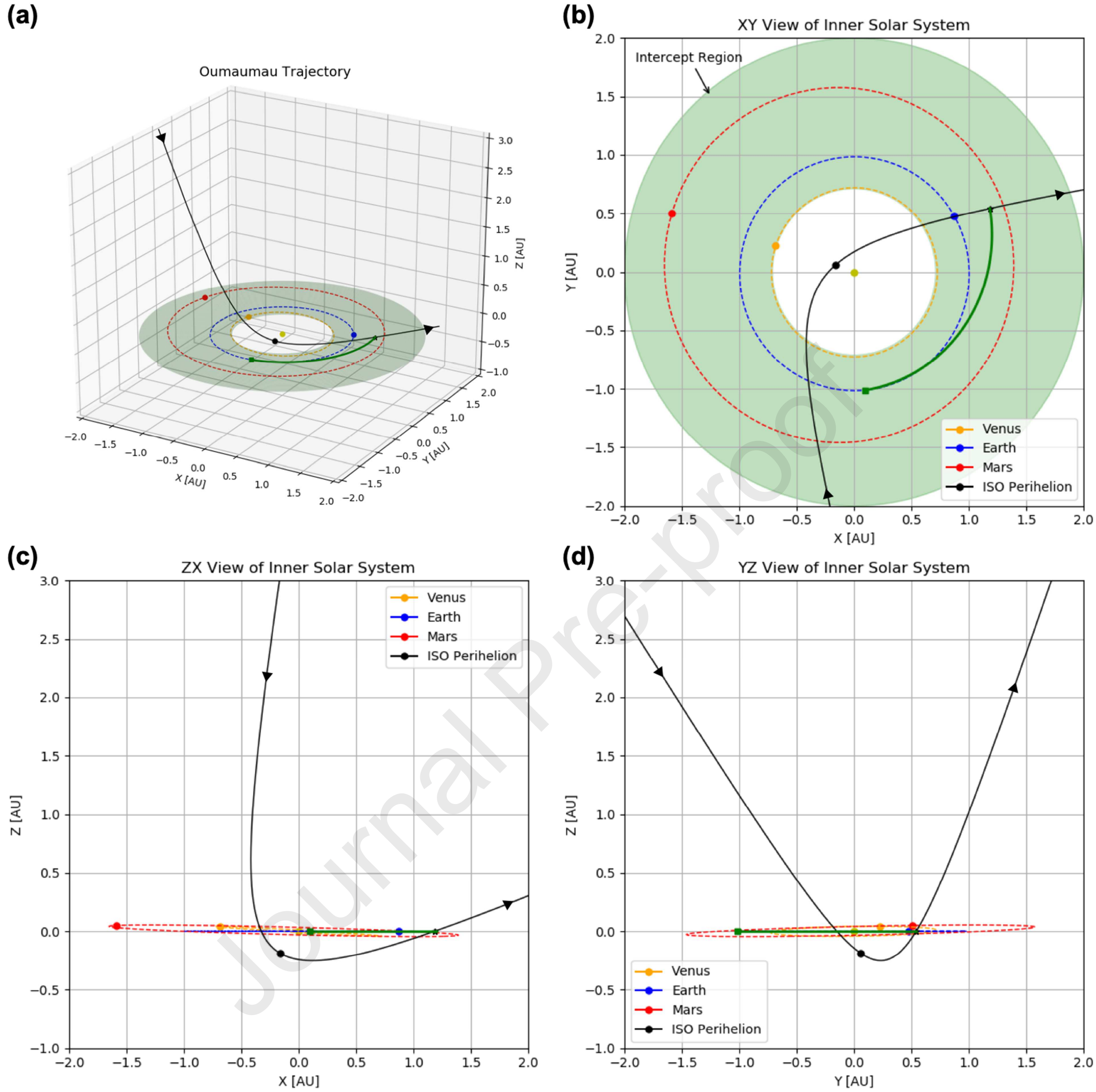
4.1.2 Target selection criteria

As part of the mission design to encounter an as-yet undiscovered ISO, Bridge would use a set of go/no-go criteria in order to determine whether a newly detected ISO would be a feasible target. Because Bridge is designed around an inner solar system intercept, the first criterion is that Bridge must encounter the ISO within the spherical shell of space between 0.7 and 2 AU from the Sun



(see Section 6.1.2 for discussion on this trade); in reality, the spacecraft would remain close to the ecliptic due to energetic constraints. The second criterion is that the Bridge spacecraft and the ISO must have a relative encounter velocity of less than 70 km/s. The need to allow encounter velocities this high is driven by large inherent speeds of incoming interstellar objects; 1I/'Oumuamua and 2I/Borisov reached approximately 90 km/s and 45 km/s at perihelion, respectively. A velocity of 70 km/s is a reasonable upper bound to ensure adequate data collection and quality while not detrimentally restricting the number of potential targets that Bridge could reach. We explore the effect of raising or lowering this bound in Section 6.1.2. Finally, the last criterion is that the total Δv for the mission must not exceed the physical limits of our chosen launch vehicle and the mass of our spacecraft (i.e. it must be possible to reach the ISO). Figure 4 illustrates a hypothetical inner solar system encounter with 1I/'Oumuamua that meets all the aforementioned criteria with a launch date of 6/27/2017, an intercept date of 10/22/2017, a time of flight of 116.85 days, a required Δv from Earth's orbit about the Sun of 4.456 km/s, and a relative intercept velocity of 55.97 km/s. This trajectory is 33 days longer than that presented by Seligman and Laughlin (2018), however we note that they launch and wait in the L1 Lagrange point, while Bridge would launch directly from Earth.





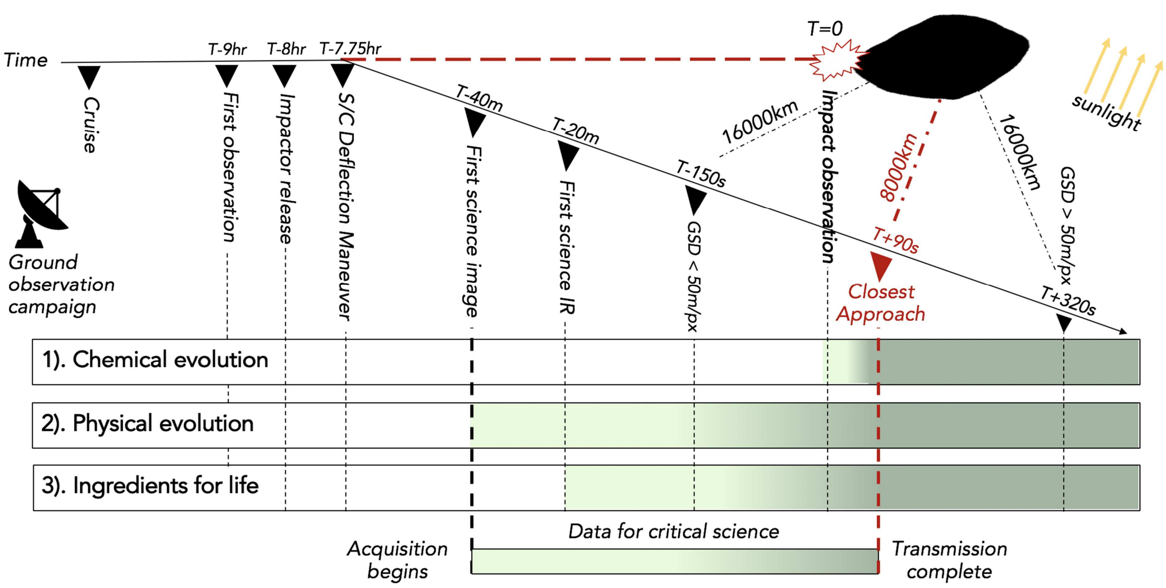


Figure 4. 3D (a), xy (b), xz (c), and yz (d) view

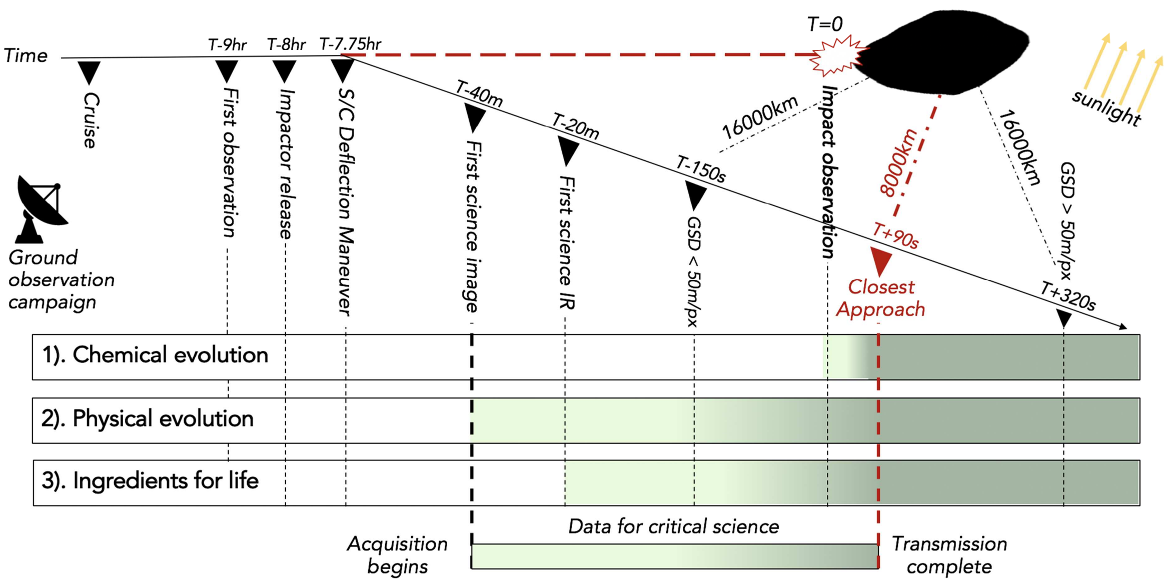
s of 1I/‘Oumuamua’s hyperbolic trajectory (black) through the solar system along with a possible intercept trajectory (green) at 1I/‘Oumuamua’s ascending node where the x, y, and z axis are defined in the ecliptic plane. Figures (a) and (b) also depict the feasible intercept region for the Bridge mission (green).

4.2 Concept of operations

4.2.1 Main spacecraft flyby encounter concept of operations

The spaceflight concept of operations (conops) for Bridge includes three phases: ISO inbound cruise, ISO flyby, and ISO outbound cruise. In the inbound cruise, the spacecraft would directly depart Earth’s gravity well on a direct transfer to the ISO flyby location between 0.7 and 2 AU. During this phase, instruments would be calibrated in preparation for the flyby, necessary trajectory correction maneuvers would be performed, and the spacecraft systems would be regularly checked to assure full operational capabilities during the flyby. Bridge would also begin taking optical navigation measurements to ensure necessary trajectory corrections would be made to intercept the ISO.

The flyby sequence includes three main operational milestones: impactor release, spacecraft deflection maneuvers, and closest approach. The primary goal for the flyby sequence is to maximize the scientific data transmitted to Earth prior to the highest risk portion of the flyby — the closest approach of the main spacecraft to the ISO. For the following description and the schematic in Figure 5, we assume a flyby scenario of 70 km/s relative velo city and an ISO of simil



ar size or larger to 1I/'Oumuamua. Although a slower flyby scenario could allow closer flyby geometries and greater observation time, we have designed Bridge such that all science questions could be addressed up to a maximum flyby velocity of 70 km/s (see Section 6.1.2 for a discussion of other maximum relative velocity choices). Note that the instruments require a geometry where the spacecraft is placed between the ISO and Sun during the flyby so that the illuminated ISO region faces the spacecraft.

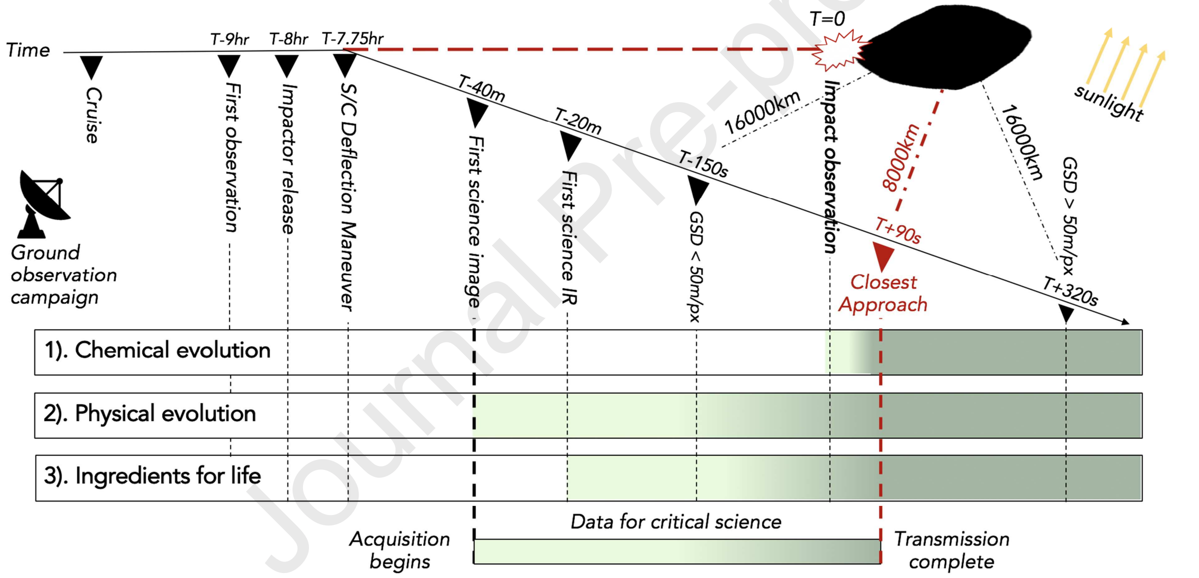
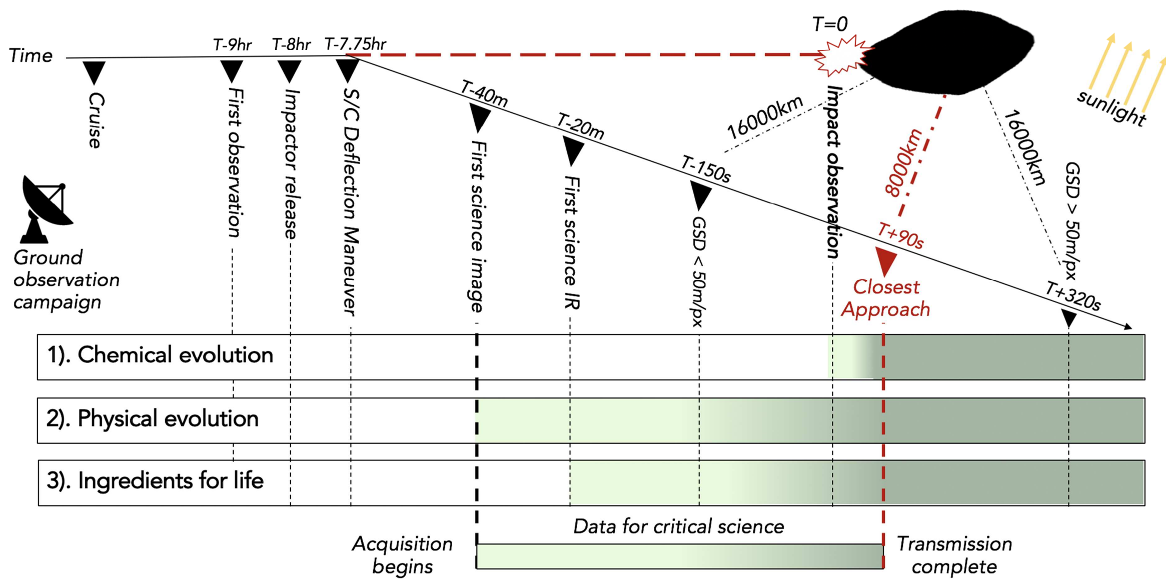
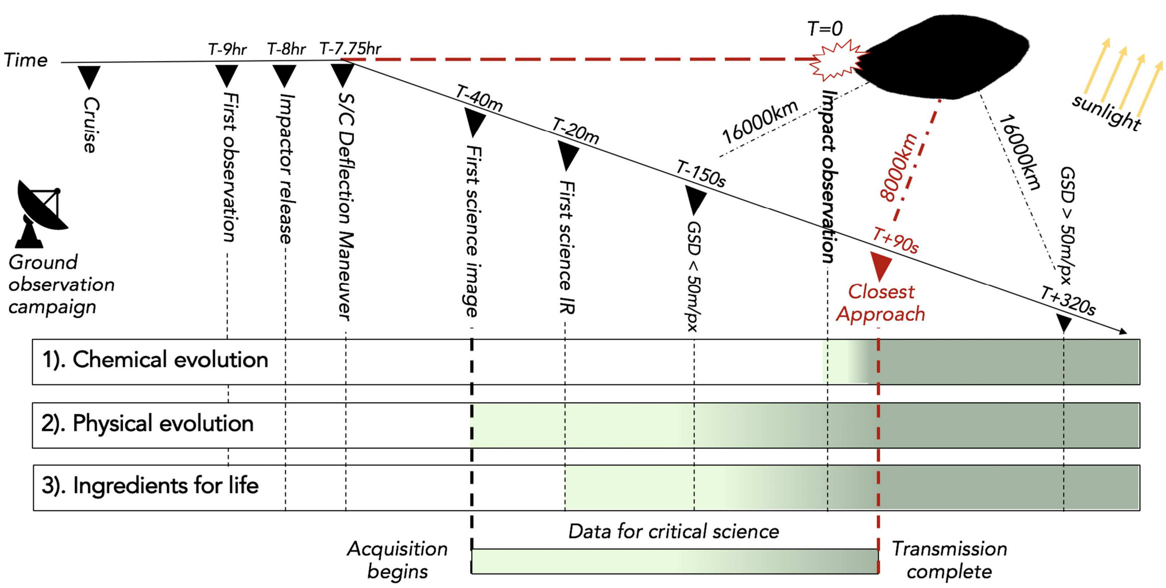


Figure 5: Concept of Operations (conops) of the main spacecraft (black solid line) and the impactor (red dashed line) during the ISO encounter. Time is shown along the top axes relative to the time of impact (T=0). Spacecraft observations and data acquisition are tied to the three science objectives along the bottom of the figure. The first dashed line on the



science objectives represents the start of data acquisition/transmission, and the red dashed line represents the completion of mission critical data collection/transmission. Color gradients represent the progression of the data collection/transmission. All data for critical science for each science objective would be transmitted back to Earth before closest approach.

In a 70 km/s flyby scenario, the ISO would first be visible by the spacecraft approximately nine hours prior to closest approach. At that time, final pointing slews would put the impactor on track to collide with the ISO and imagery would be transmitted to Earth. Approximately one hour later, the impactor would be released from the main spacecraft, and the main spacecraft would perform a deflection maneuver which would steer it to a designated closest approach distance of 8000 km. This distance is necessary to reduce pixel smear as the main spacecraft slews to keep the ISO in view as it flies by at 70km/s. However, this distance could be reduced for slower encounters; specific mission actions to mitigate the potential risk created by close proximity to impactor-generated dust may be addressed in follow-on studies. At 45 minutes prior to impact, the ISO would be larger than a single pixel on the imagers of the spacecraft and impactor. At this time, all instruments would begin acquiring data. Thirty seconds prior to impact, the IR spectrometer and impactor optical camera would observe the surface composition. The visible camera on the main spacecraft would capture continuous images over the impact period that could be made into a video showing the moment of impact, and the UV spectrometer would image the ejecta plume flash with a high repetition rate. Following the impact, the IR spectrometer would also make measurements of the plume. The main spacecraft's closest approach

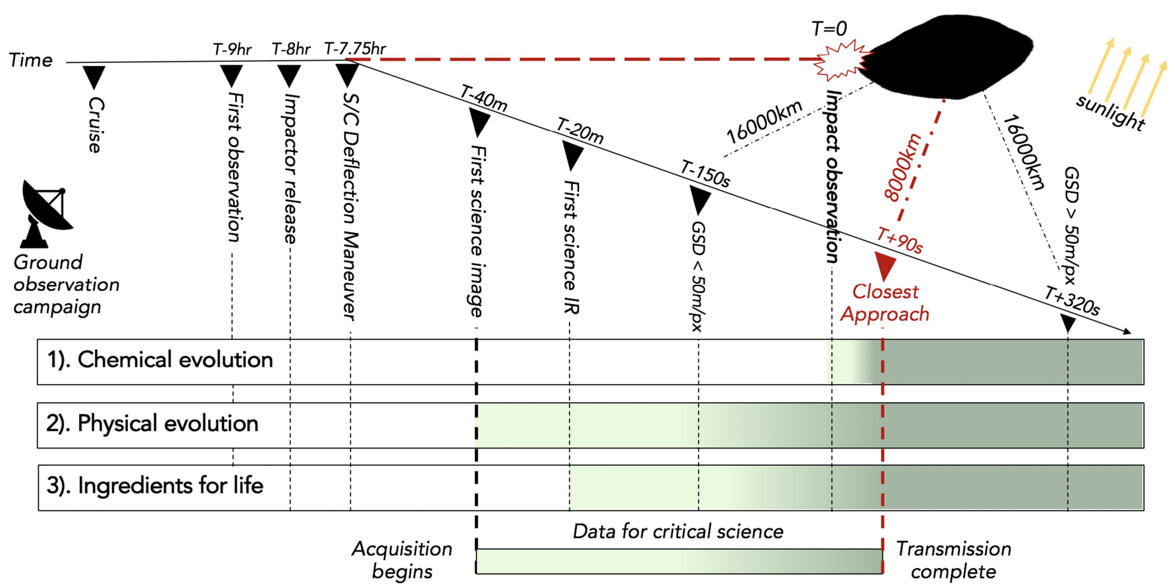


oach would occur 90 seconds after impact. The sensor measurements of the impact and select images from the visible imagers onboard both spacecraft would be transmitted to Earth prior to closest approach, leading to mission success before the highest risk segment of the flyby. Continued observations would be made after closest approach until the ISO was no longer resolvable. Data collected after our closest approach could likely still be usable for science.

After closest approach, during the outbound cruise, the spacecraft would complete data transmission of all other measurements to Earth and perform any mission ending sequences required. Since we have designed our mission to avoid the primary physical hazards at close approach, the Bridge spacecraft should still be in good health and able to pursue an extended mission if there is a favorable trajectory and sufficient fuel remaining to reach a secondary target.

4.2.2 Impactor concept of operations

As shown in Figure 5, the impactor release from the main spacecraft occurs eight hours before impact. Once released, the impactor would coast for six hours at which point the impactor's auto-navigation (AutoNav) would begin. The impactor's AutoNav calculates three trajectory correction maneuvers at T-90 min, T-35 min, and T-10 min using visual images of the ISO taken by the onboard camera to ensure impactor collision with the ISO. During its intercept trajectory with the ISO, the impactor is in constant communication with the mothership transmitting high-reso



lution images back as additional science data.

5. Mission implementation

5.1 New Frontiers requirements

We design Bridge as a *New Frontiers* class mission. The NF4 AO (NASA, 2016) imposes a cost cap of $850M in NASA FY 2015 dollars for Phases A through D, not including the cost of an Expendable Launch Vehicle (ELV) or any contributions. Our analysis was performed in FY 2019 dollars, with the cost cap inflated to $930.1M using NASA inflation rates. The cost estimation is performed using JPL and NASA Institutional Cost Models utilizing heritage actual costs and One NASA Cost Engineering database; Table (3) shows a breakdown of the mission cost according to Phase. The NF4 AO requires a minimum cost reserve of 25%; our mission comfortably fits the cost cap with 46% development cost reserves (Phases A-D). This includes the launch vehicle penalty for using a 5m fairing rocket instead of the standard vehicle, as specified in the AO. The baseline mission design explicitly budgets for spacecraft storage in a clean room facility as well as a trained launch team on standby for up to seven years. Although some spacecraft have been stored in cleanroom facilities before, this is usually unintentional and due to delays or a lack of funding. Thus, there are few prior examples of intentional long-term ground storage, which adds uncertainty to cost estimation. Additionally, whil

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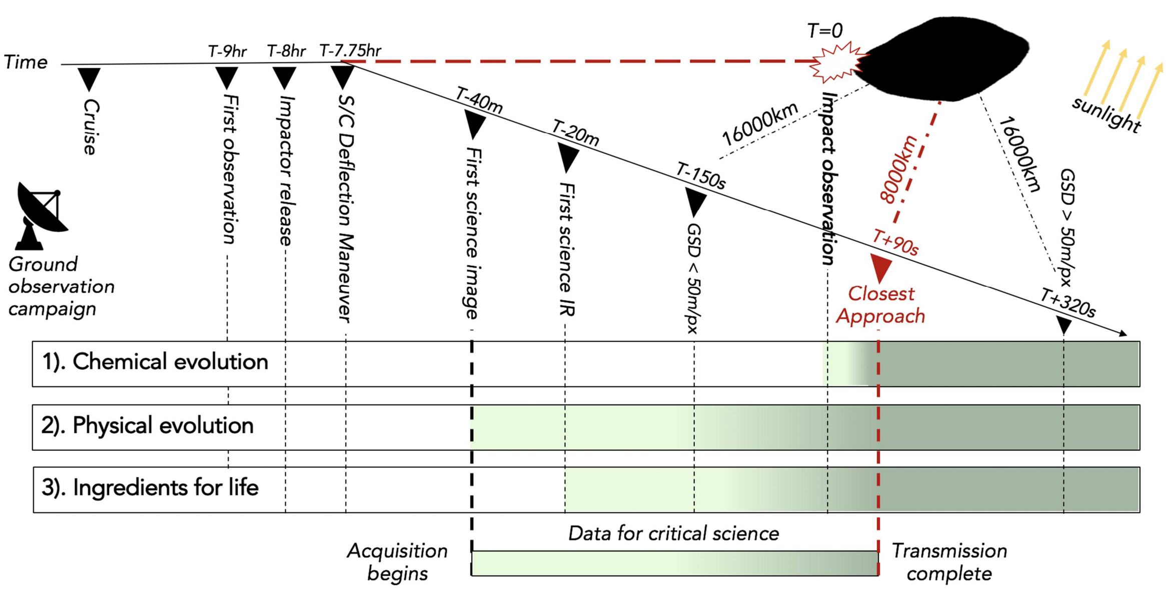
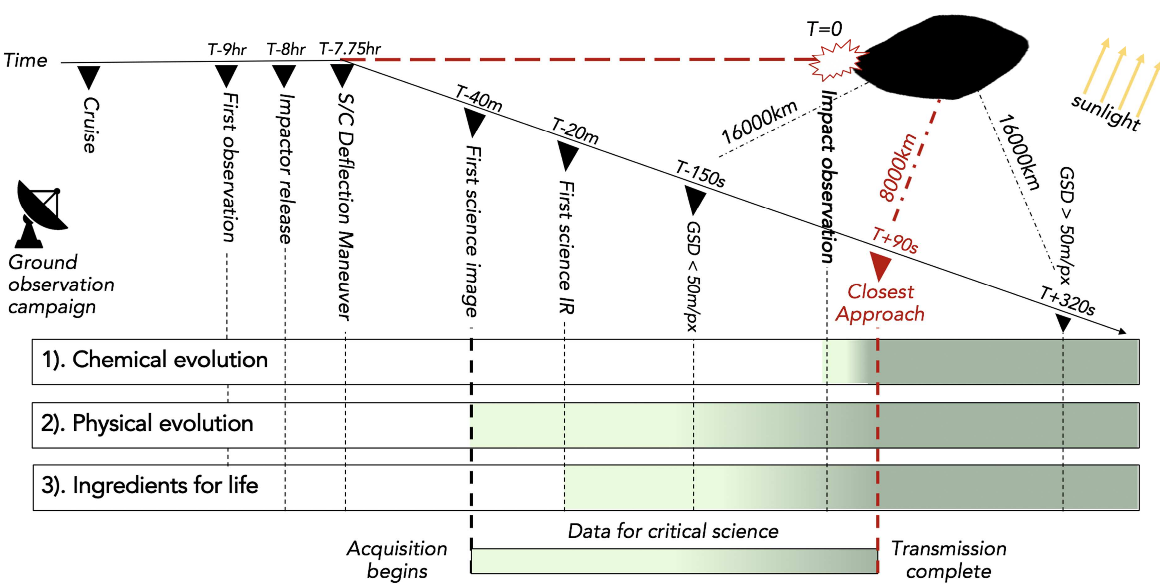


on our current assumptions of arrival and discovery rate of ISO's (see Section 6.1.2), it is possible it may take more than seven years to discover a reachable ISO, adding further uncertainty to the expected cost. The built-in high cost reserve significantly decreases the likelihood of cost overruns due to these uncertainties.

We estimate the cost of each instrument using the NASA Instrument Cost Model (NICM) with historical analogs and minor modifications. Deviation from mission heritage for the impactor and the Mid IR Point Spectrometer is accounted for in allocating the funds necessary to increase their Technology Readiness Levels (TRL) from 5 to 6.

Table 3: Mission Cost Breakdown in FY 2019 dollars

Cost Summary (FY 2019)	Reserves	Cost (M)
Project Cost	**43%**	**$973.1**
Launch Vehicle Capability (penalty)	0%	$22
Development cost (Phase A-D)	**46%**	**$930.1**
Phase A		$4.0
Phase B		$86.8
Phase C/D		$817.3
Operations Cost (Phase E-F)	**15%**	**$43.0**



5.2 Spa cecr aft desi gn

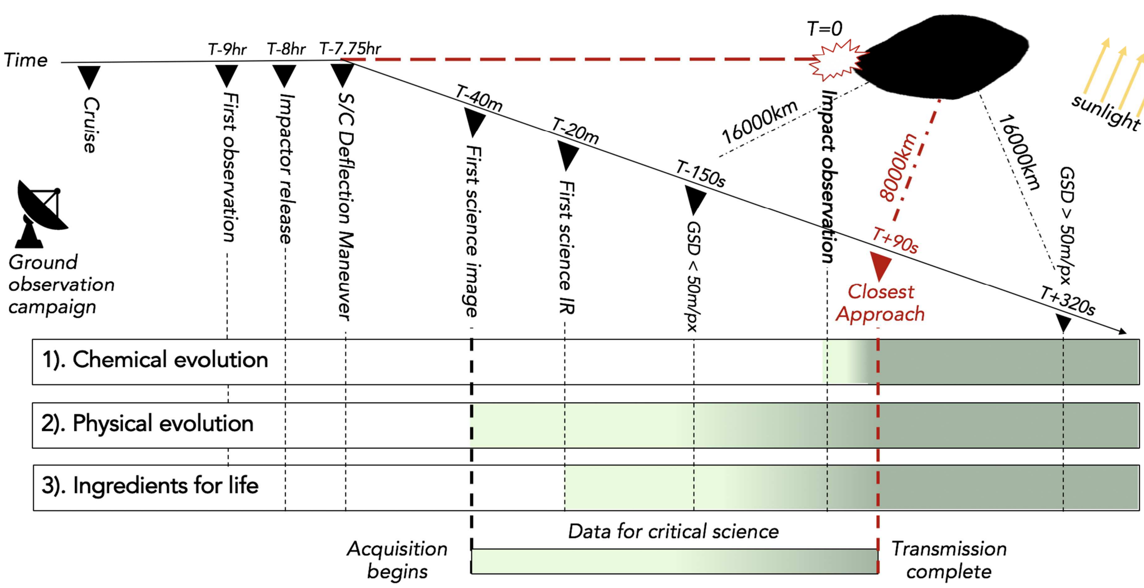
The spacecraft design is based on the heritage of previous spacecraft, reducing risks and costs. The dry mass of the spacecraft would be 890 kg, including a bus of 550 kg and a payload of 340 kg (including a 250 kg impactor). With propellant, the total launch mass of the spacecraft would be 1108 kg, which leaves a comfortable launch vehicle mass margin of 82 kg using the Atlas V 531 rocket. The following sections provide more detail on individual systems.

5.2.1 Propulsion

The Bridge spacecraft would employ a hydrazine (N_2H_4) monopropellant propulsion system operated in blow-down mode for all of the proposed trajectory correction maneuvers (Fig. 5). Additionally, the monopropellant system would provide attitude control during the cruise and post-encounter phases. A single primary thruster would perform Trajectory Correction Maneuvers (TCMs), and minor attitude control operations would be executed using twelve additional thrusters. The distribution of thrusters upon the spacecraft would allow for three degrees of freedom in rotation and two in translation during maneuvers. The simple blow-down system and thrusters are based on currently available commercial parts (e.g. the Aerojet MR-111C and MR-107T thrusters), and provide sufficient propulsion for the relatively short proposed mission duration for an encounter with an ISO in the inner solar system.

5.2.2 Power

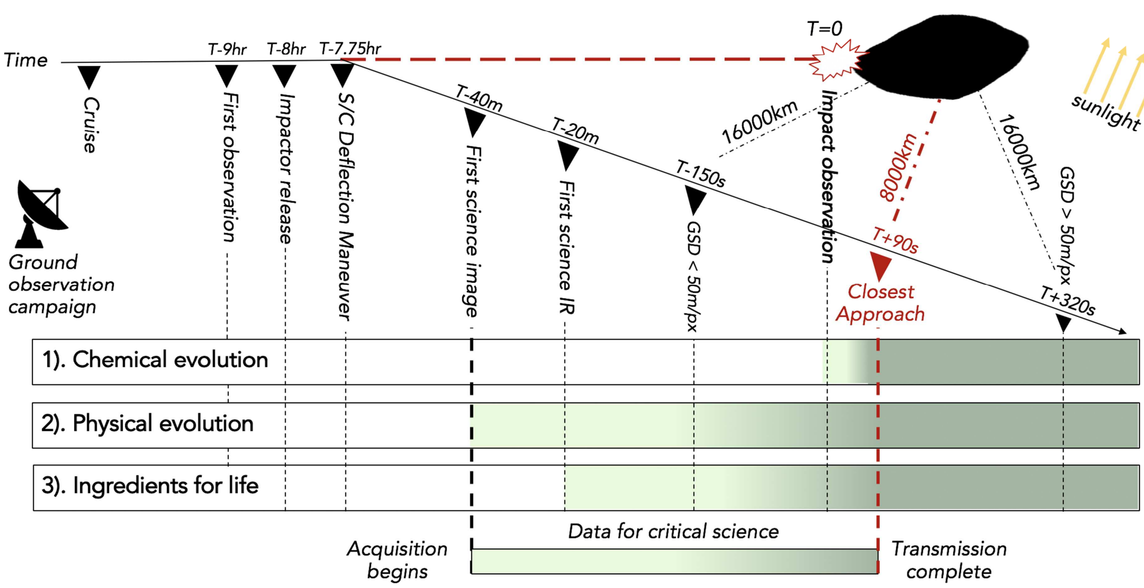
Articulated solar



panels and a secondary battery would provide power to Bridge's subsystems and instruments. Two deployable gallium arsenide solar panels would each have an area of 5 m^2, and would produce power with 29.5% efficiency during the cruise to the interstellar object. The solar panels would be articulated with one degree of freedom to allow independent pointing towards the Sun. During the flyby, the 34 Ah lithium ion secondary battery would supply the power needs of the spacecraft. The battery would only be required twice: during launch and during the high-speed flyby. The battery capacity would be sufficient to complete all phases of the flyby, including post-encounter communications downlink, while maintaining a discharge level greater than 37%. The standard JPL reference bus, at 28 V, would distribute power to the spacecraft subsystems and instruments. The proposed power system follows in the footsteps of other inner solar system missions, including Venus Express (Svedhem et al., 2009) and Mars Odyssey (Saunders et al., 2004).

5.2.3 Thermal Systems

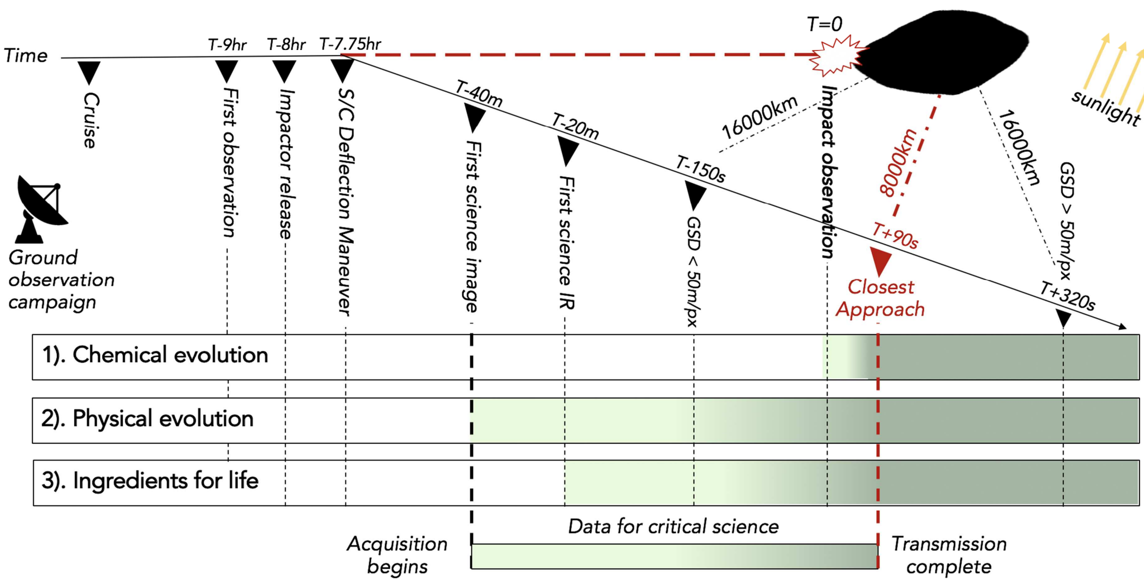
Bridges thermal system would utilize a straightforward combination of active and passive heating to accommodate instrument demands. Active cryocooling would sufficiently cool the infrared instruments while a passive radiator would keep the ultraviolet instrument at room temperature. Passive cooling combined with electrical resistance heaters would keep the core spacecraft electronics between -20° C and 50° C, which is suitable for an inner solar system encounter.



5.2.4 Attitude control systems

The Bridge spacecraft's attitude control system (ACS) design is driven by the high pointing requirement tolerances during the impactor release and science phases of the mission. In order to meet mission requirements, the Bridge spacecraft must be able to accurately determine the relative position of the spacecraft and the ISO for targeting the impactor, guarantee the ISO is inside the FOV of the instruments, and continuously track the ISO during the science phase of the mission to collect the necessary scientific data without instrument smear from slewing.

Throughout the mission, the spacecraft's attitude would be controlled via a combination of three 12 N-m-s HR12 Honeywell reaction wheels and twelve 1-lbf Aerojet MR-111C RCS thrusters. During the launch, cruise, and post-encounter phases of the mission, the spacecraft's attitude would be controlled solely by the twelve RCS thrusters due to the more relaxed pointing requirements. A 10° thruster deadband during cruise and a 1° thruster deadband during TCMs is sufficient for the pointing requirements during each of these mission phases. During the impactor release and science observation phases, which require a higher degree of pointing accuracy, the spacecraft's attitude would be controlled by the three reaction wheels to an accuracy of 0.3 mrad (i.e., 3/10th the field of view of the UV/VIS Spectrometer), which ensures that the ISO is within the FOV of all the science instruments to a safety factor of three during the science observation phase.



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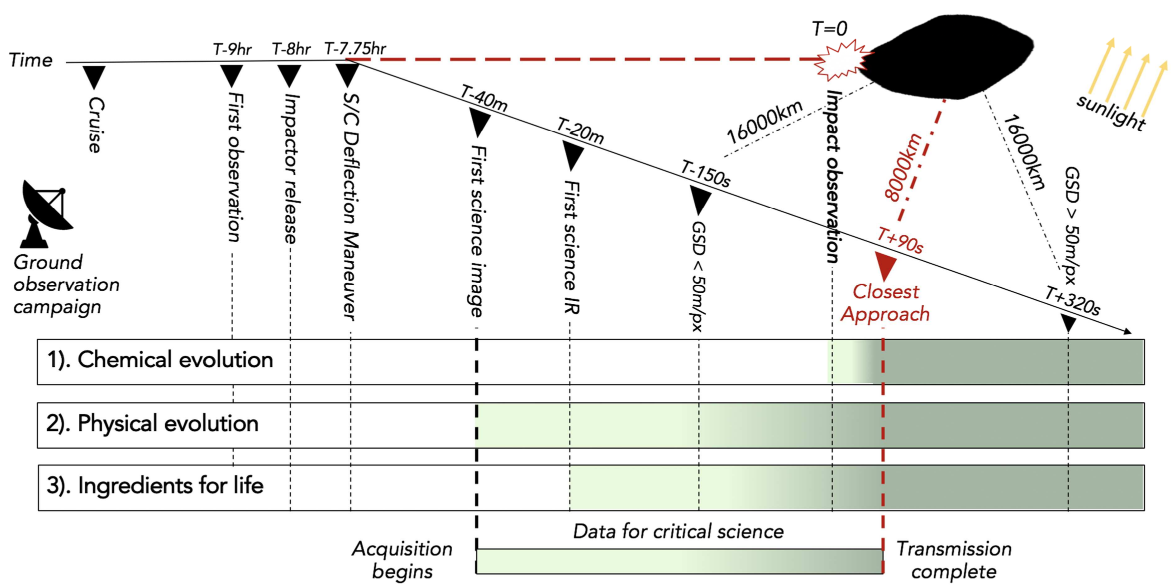
ely determine the relative position of the spacecraft and the ISO for impactor targeting, the Bridge spacecraft's attitude would be determined using a combination of two Galileo AA-STR star trackers, two Adcole two-axis coarse sun sensors, and two Honeywell miniature inertial measurement units (MIMUs) for redundancy. The combination of these three subsystems provides attitude knowledge to 0.03 mrad. Current specifications for the spacecraft assume inertial pointing. To increase the fidelity of the design, an in-depth look at the necessary hardware/software such as optical navigation and autonomous tracking for both the spacecraft and impactor would be needed for formal mission implementation.

Finally, when designing the ISO encounter with a relative velocity of 70 km/s as described in Section 4.1.2, the Bridge spacecraft needs to rotate 180° over the course of the encounter for continuous science observations. In order to keep the slew rate around 0.5 °/sec, which is assumed to be the upper bound on the turning rate of a normal spacecraft, a flyby with a closest approach of 8000 km or farther is required. The slew rate for the Bridge spacecraft during the ISO encounter can be seen in Figure 6. No imaging would occur during the turning of the spacecraft.



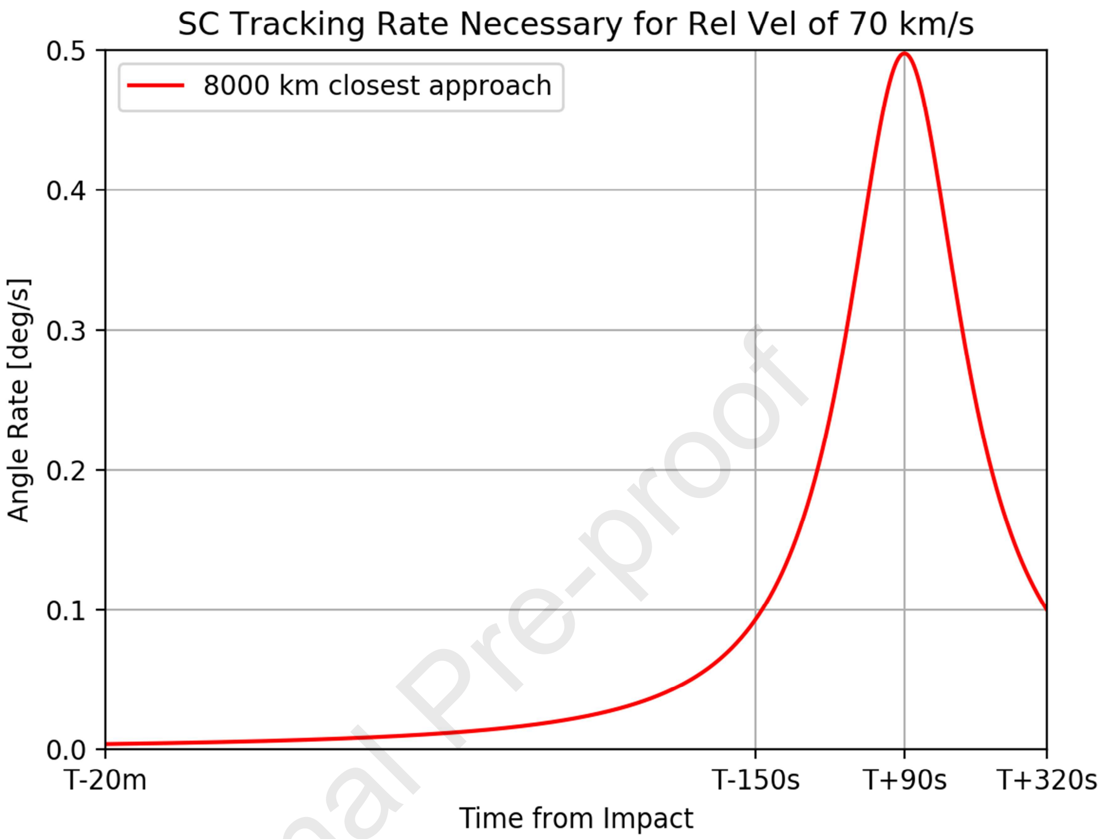
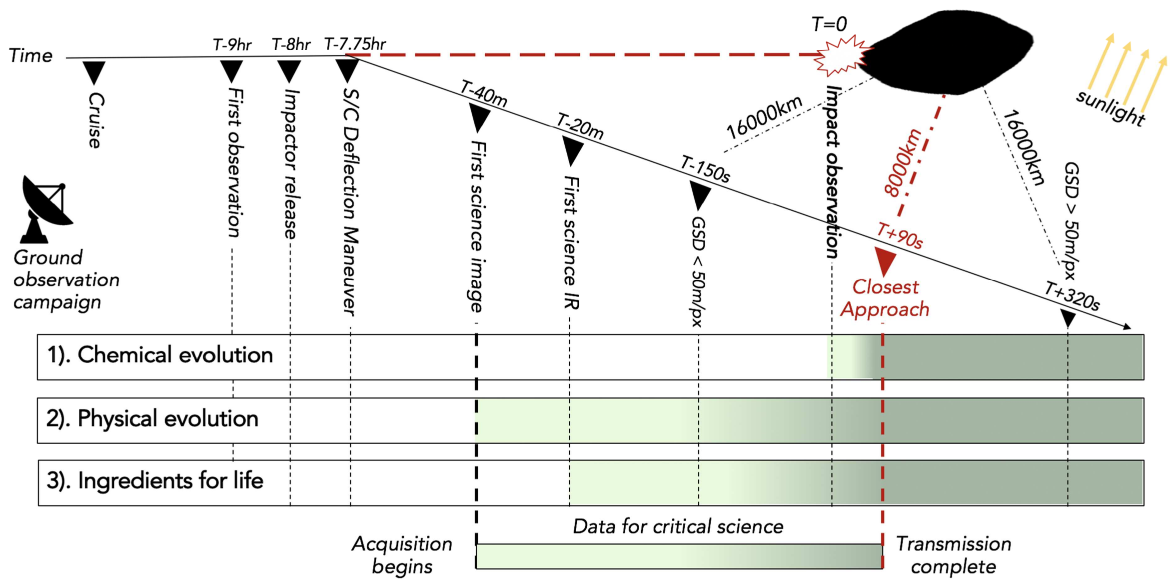


Figure 6: The Bridge spacecraft's slew rate during a potential ISO encounter with a relative velocity of 70 km/s at a distance of 8,000 km.

5.2.5 Command and Data Handling

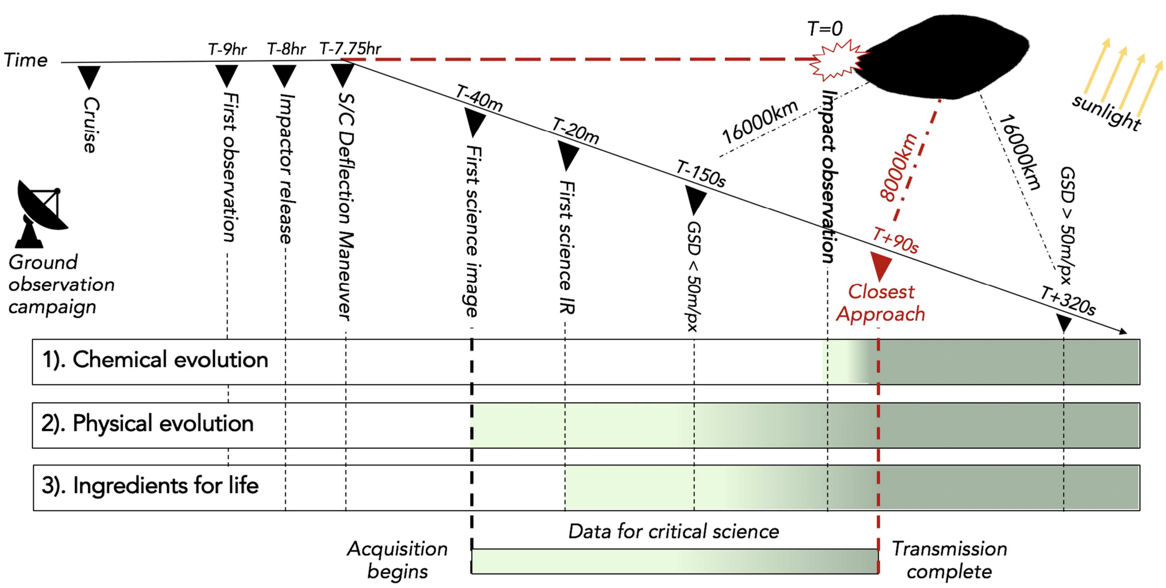
Bridge would include a standard central processing unit (CPU), memory, communications, analog, and



digital systems. The standard procured 200 GB memory card for onboard data storage would readily accommodate the 7455 Mb of data estimated to achieve the baseline science objectives, out of which only 172 Mb are required to meet the critical science requirements. The two-order of magnitude margin of extra onboard data storage also allows for flexibility in the size of the currently unknown target. Bridge would transmit all data required for critical science before closest approach (Section 4.2), and the data volume budget would be dominated by large-volume images acquired by the camera (Section 3.1). The downlink requirements can be reduced by extracting imaging data on-board, and transmitting only the pixels in images that are occupied by the target (as well as those immediately surrounding the target, in order to encompass a substantial buffer for data control purposes). If on-board extraction could not detect the target from the surrounding environment, the ample storage margin would allow for the need to store whole images, which could be transmitted later. Table 4 lists our predicted data volumes based on our current instrument specifications.

Table 4. Data volume specifications for instrument payload

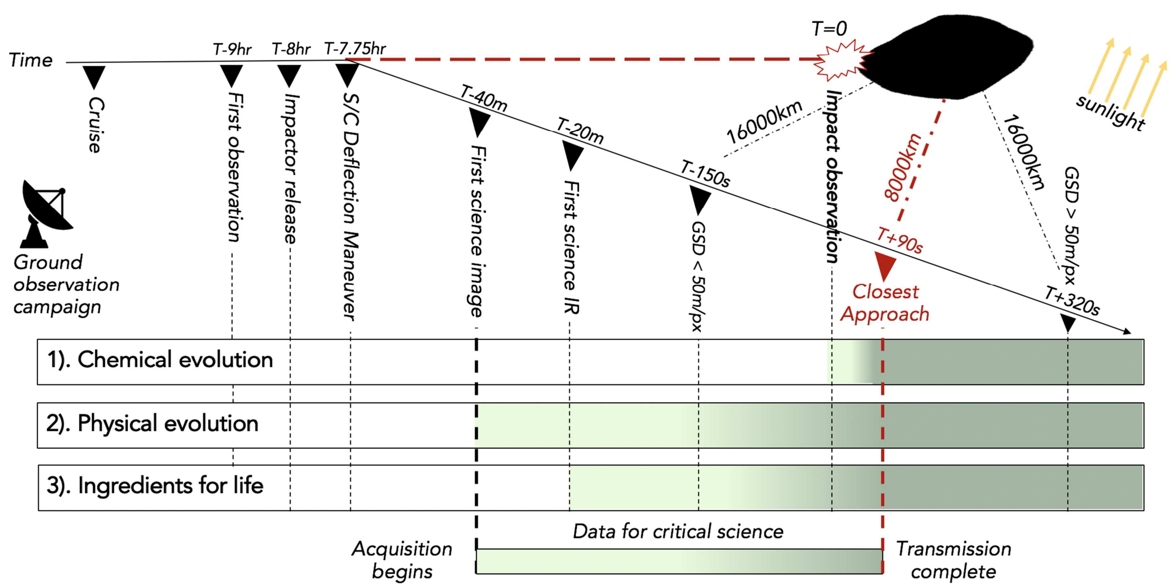
Instrument	Data Volume (Mb)
Main Camera	5033
Impactor Camera	1510
Near-IR Spectrometer (1- 4 μm)	144



Mid-IR Spectrometer (7-15 μm)	288
UV/VIS Spectrometer (200-600 nm)	480
Total	**7455**

5.2.6 Telecommunications

The telecommunications system would operate in the X-band for both direct to Earth and direct from Earth communications. The X-band is preferred for communication with Earth to ensure the return of our science data regardless of potential weather disturbances at the DSN sites. The relay link between the main spacecraft and the impactor would operate in the S-band. To this end, Bridge's radio would be an S/X-band Universal Space Transponder (UST). A 1.5 m high-gain antenna with a half-spherical view would guarantee a 120 kbps downlink to Earth at a distance of 3 au. A medium gain antenna and two low gain antennas would provide a safe-mode link. All X-band antennas would be fed by a 100 W travelling wave tube amplifier. The impactor would use an S-band 2W transmitter connected to a medium gain array of patch antennas that are identical to those used on the Deep Impact mission (Taylor & Hansen 2005). This antenna would operate in receive-only mode and provide a 30 kbps relay downlink from the impactor. The Deep Impact mission was able to guarantee 64 kbps at 8700 km, which gives an excellent reference for our flyby geometry; we use a conservative estimate here of 30 kbps, in orde r to incr eas e the link



margin on the telecommunication system.

5.2.7 Ground operations

While waiting to discover a new ISO, the spacecraft would remain in long-term storage in a cleanroom environment (such as the JPL High Bay or a commercially contracted space). During phase D building and construction, members of the ground operations team would prepare manuals and training materials for team members to re-learn once they finish on that phase of the mission. It's unreasonable to ask the full engineering team to wait around for up to 7 years for this mission to fully commence, so it's anticipated that team members will also be working on other flight projects in the meantime. Having these training manuals made would aid in re-training team members as they come back onto the Bridge project from other flight projects, or training new members.

Since this storage period would last for an unknown period of time, a small team of operations specialists would be on standby (i.e. trained members of the team who can run tests on system health and update any software that needs updating during the storage process). Ideally, this would include a lead/co systems engineer, a deputy systems engineer, as well as integration and testing team members. If the object is detected two years out, we estimate several months for characterization of the ISO's orbit and planning of the mission trajectory. Our maximum permitted turnaround time from target detection to launch is 6 months (see Section

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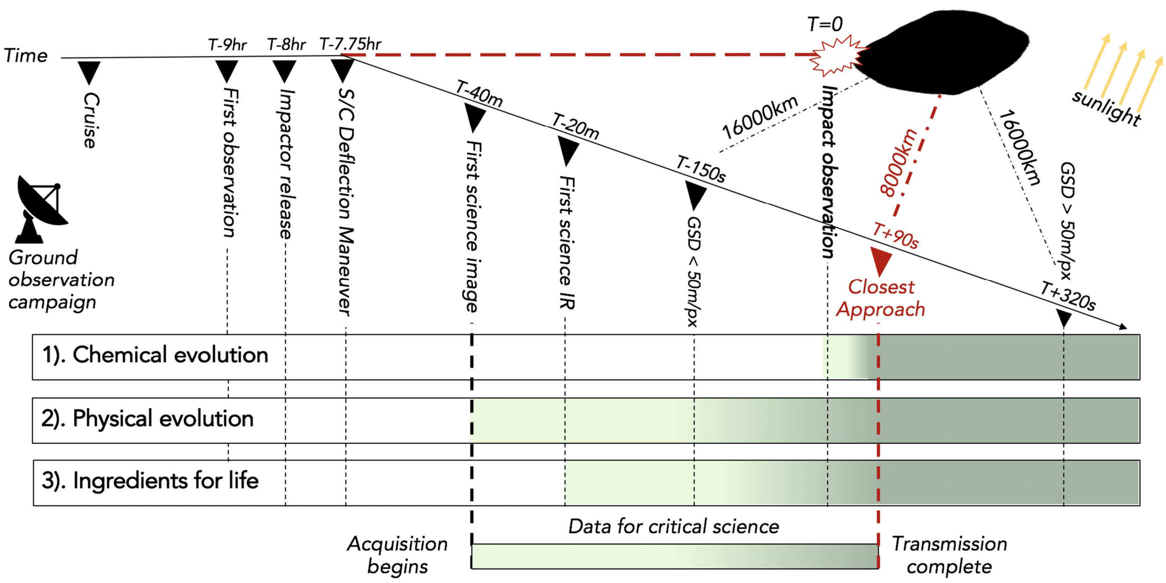
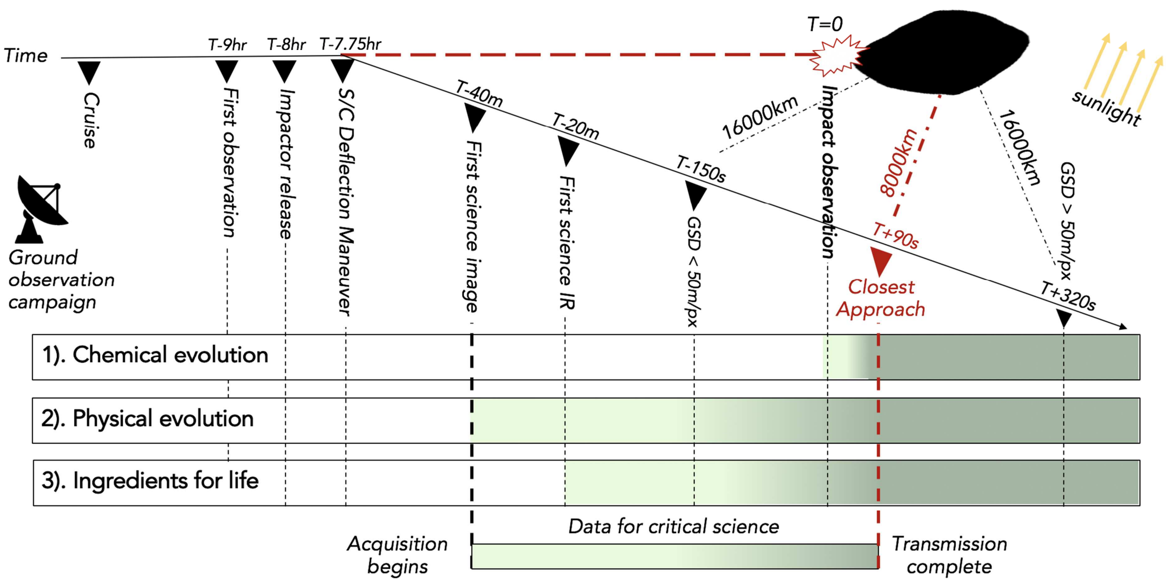


trade study comparing the mission outcomes using different turnaround times). This is the minimum time needed to prepare, test, integrate all systems with the launch vehicle, and launch the spacecraft from NASA's Kennedy Space Center. We would likely need a ready-to-use launch vehicle, since the costs of storing a specific rocket for several years could be high. A year prior to launch is preferable for more testing of the systems and scheduling on the Deep Space Network (JPL, 2015). However, a suitable object is unlikely to be discovered with suitable lead time (>> 2 years before the target's perihelion) for a one year launch turnaround time.

Launch preparations would include running tests on the spacecraft, updating system software, and uploading the initial cruise phase commands. An ideal encounter sequence would be designed and uploaded to the spacecraft ahead of time with all events fixed to the time of closest approach. We note that in our concept of operations, only one hour elapses between the first observation of the ISO by the spacecraft and the launch of the impactor. At a distance of 2 AU, transmissions would take 16.23 minutes from the spacecraft to reach the ground station and another 16.23 minutes to transmit back to the spacecraft. These are close margins for manually modifying the flight plan, but could still allow for small pointing adjustments to be made prior to encounter.

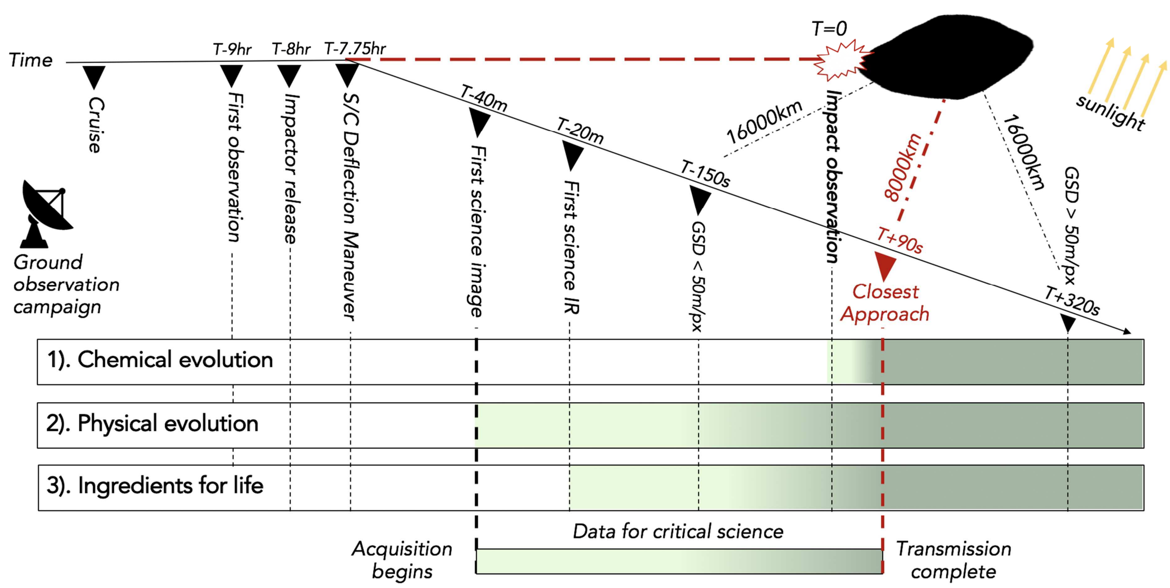
The mission team would also need to schedule time with the Deep Space Network (DSN). Since the ISO encounter would be a critical event for the mission, Bridge could utilize two 34m DSN antennas for



coverage of the ISO encounter event, and possibly the 70m DSN antenna as a backup to ensure that all data would be returned to the ground. Bridge would utilize standard NASA AMMOS (Advanced Multi Mission Operations System) software for the ground operations strategy with some new routines written specifically for the mission's encounter phase.

5.2.7 Mechanical/Structures/Configuration

A standard rectangular bus, similar to the Mars Global Surveyor and Dawn spacecraft, would house Bridge (Albee et al., 2001; Russell et al., 2007). Reaction wheels would be mounted on the interior of the bus, along with a strut-mounted hydrazine propellant tank. The spacecraft would have a deployable boom for the high gain antenna, which would also be on a 2-axis gimbal. All instruments are mounted on one side of the bus as illustrated in Figure 7.



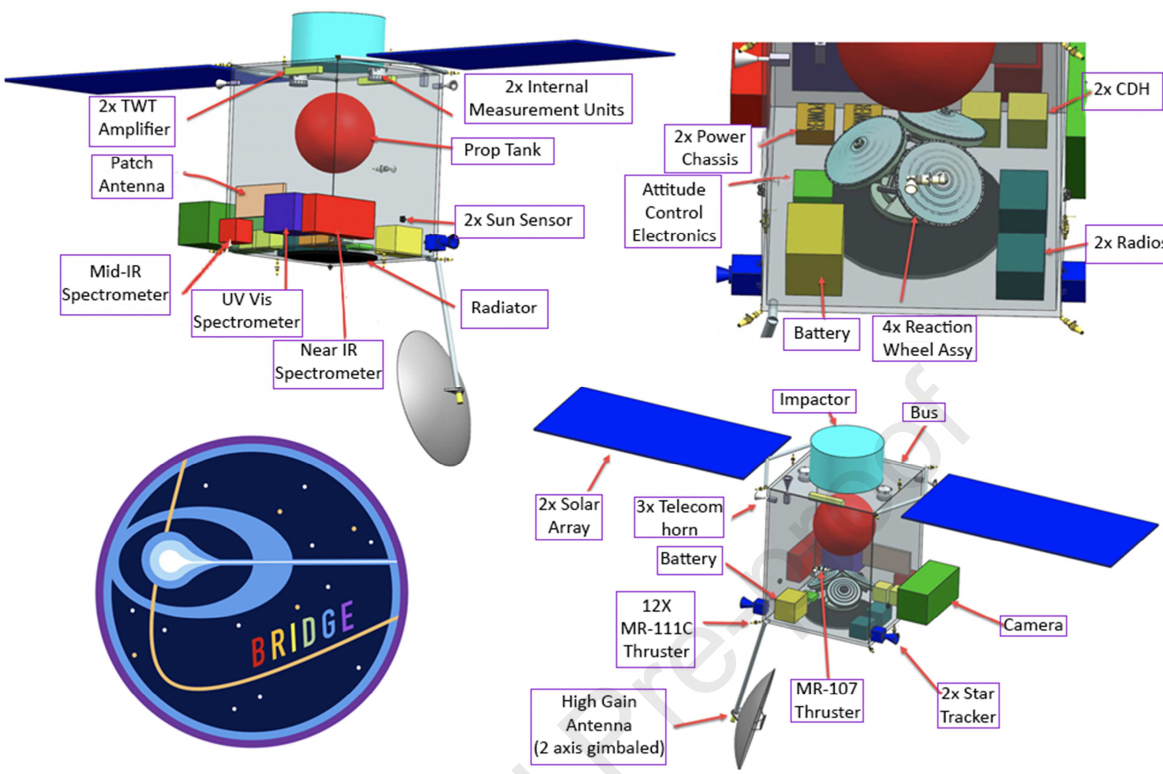


Figure 7. Overview of spacecraft bus and configuration with instrument payload shown. Each view of the spacecraft bus represents a different viewing angle for the viewing of all relevant components.

6 Discussion:

6.1 Key Trades

Because the existence, properties, and trajectory of Bridge's target ISO would only be

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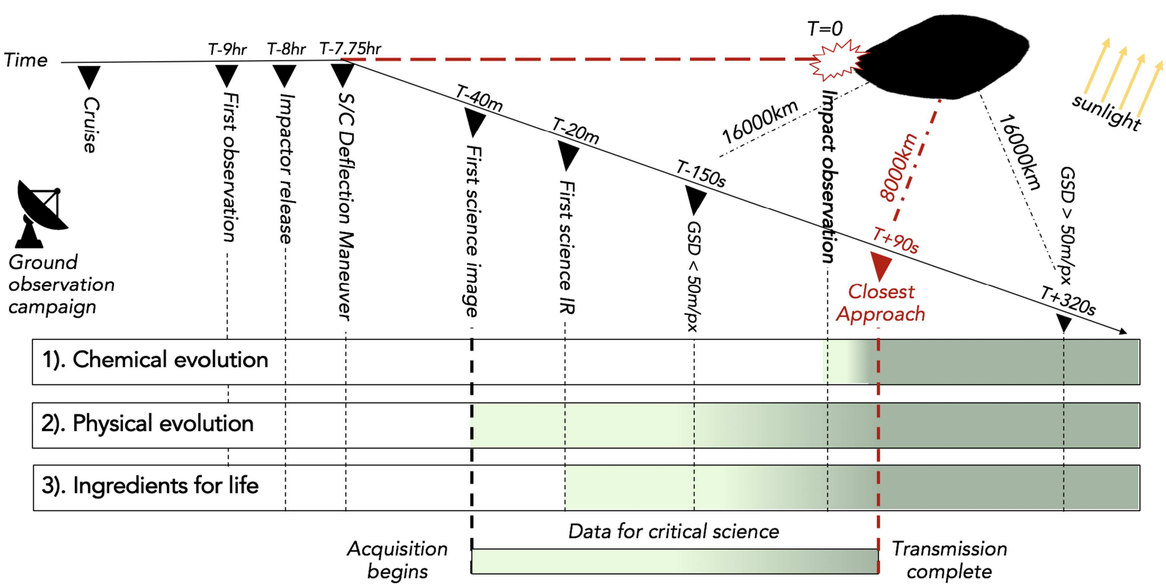
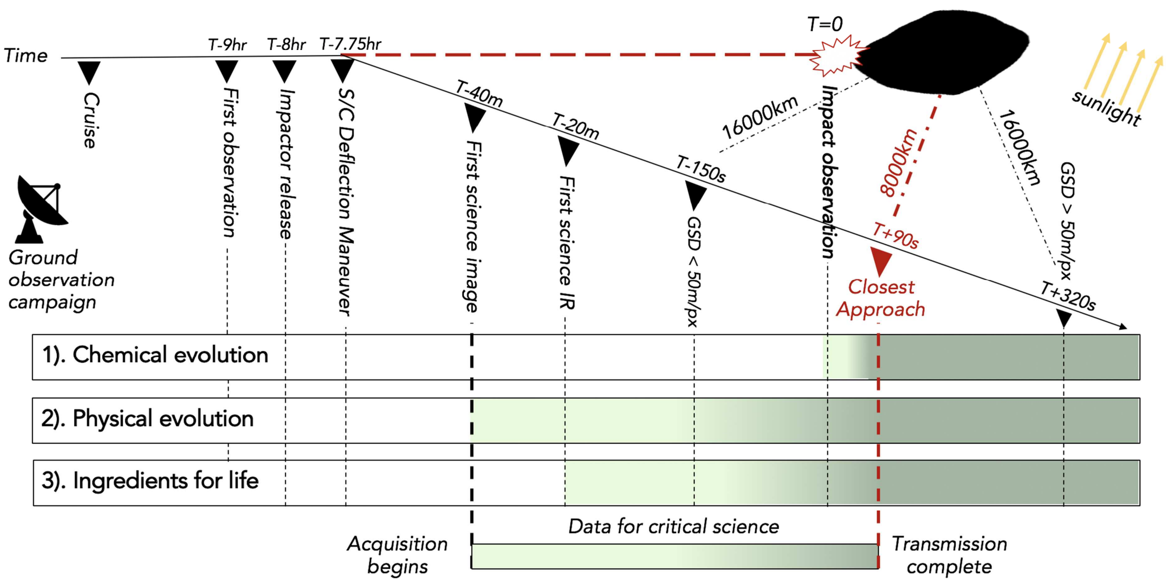


re launch, Bridge must consist of a flexible low-mass spacecraft design and instrument suite that is capable of characterizing a variety of objects with a wide range of potential properties. Here we discuss the key trades that shaped the design choices of the Bridge mission: the instrument payload, including data downlink and approach distance considerations (6.1.1); launch criteria, including whether to encounter the object in the inner or outer solar system and the role of RTGs versus solar panels for power (6.1.2); and whether to store the spacecraft at the launch site or at an appropriate Lagrange point (6.1.3).

6.1.1 Instrument trades

Here we outline the key trades we made in order to design a flexible payload capable of addressing the aforementioned science objectives during a short flyby ISO encounter. We initially considered including an *in-situ* mass spectrometer instrument in order to unambiguously identify the ISO's chemical composition. Mass spectrometers have played key roles in many past and upcoming spacecraft missions. For instance, the Surface Dust Analyzer (SUDA) instrument that will be flown as a part of the Europa Clipper mission (Kempf et al., 2015, Kempf 2018) is designed to detect species in dust grains, while the Cassini Ion and Neutral Mass Spectrometer (Waite et al, 2004) allowed for the detection of species and ions in the gas phase.

These examples illustrate many possible advantages of mass spectrometers, but were larg ely desi gne d for enc



ounters at much lower relative velocities than a mission to an ISO might entail. Nevertheless, some heritage exists; the Giotto mission employed three different kinds of mass spectrometers (ion, neutral, and dust) during its high speed (max 68 km/s) encounter with Halley's comet. These mass spectrometers all successfully obtained elemental abundance measurements (Reinhard, 1986); isotopic abundances would be similarly plausible. Collectively, such atomic measurements of in situ samples would be greatly beneficial in studying interstellar objects, and fulfill a similar science role to that of our UV spectrometer.

Obtaining measurements of organic matter during a high-speed encounter would be substantially more challenging than measuring atomic and isotopic abundances, however. This is due to the fragmentation of the material at high speeds: larger organic molecules break into shorter chains or even individual atoms, which can pose challenges for identifying specific parent molecules. The strength of this effect depends on several factors including the encounter speed and type of mass spectrometer used. For dust mass spectrometers, laboratory studies have shown that while some organics can survive impacts at speeds of 10km/s-35km/s (Srama et al., 2009), the impact cloud becomes dominated by atomic ions above ~30km/s (see Fielding et al., 2015), preventing the identification of individual organic compounds. Successfully identifying organic compounds on an interstellar object with a dust spectrometer may require a low-velocity encounter (which is statistically unlikely given current detection and propulsion technology; see Section 6.1.2) or additional research on instrument development.

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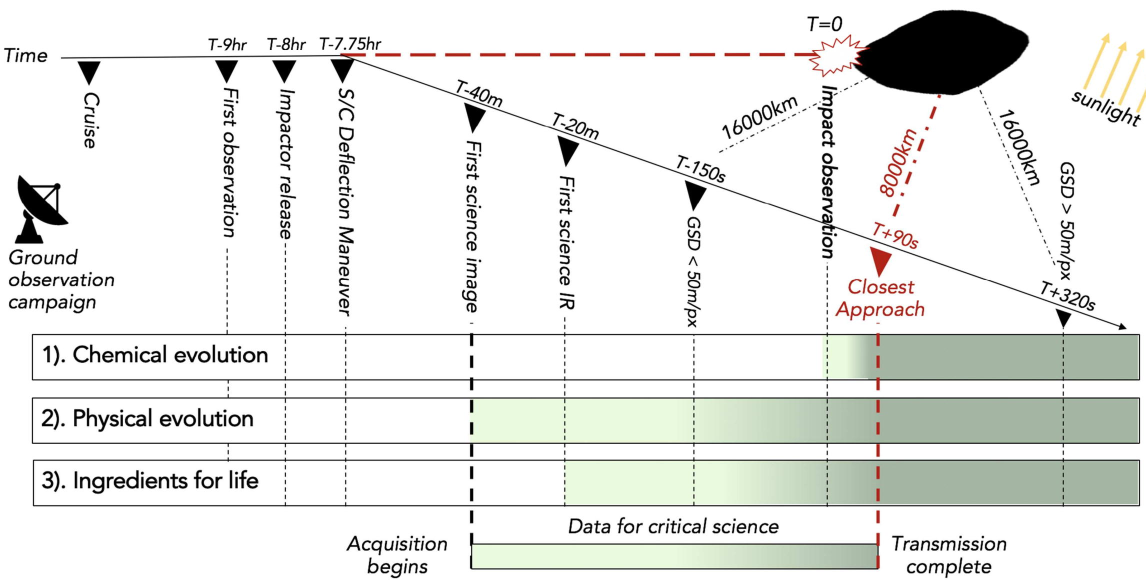

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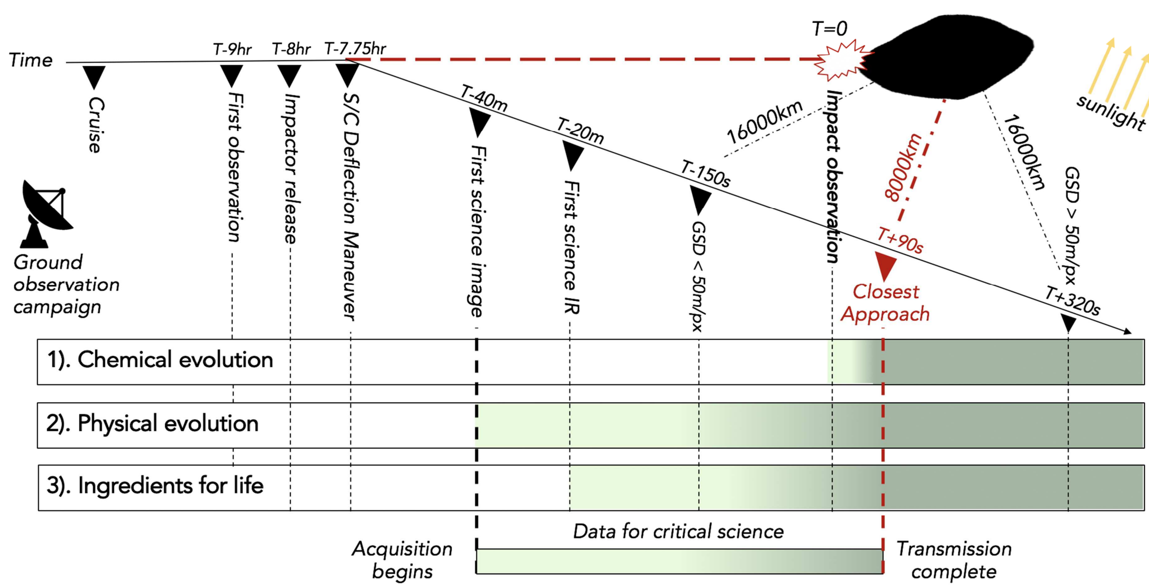
meters, we also considered the potential for ion and neutral gas mass spectrometers to measure organic species. These spectrometers have been used to identify simple organic ions such as $CH_3OH_2^+$ and H_3CO^+ (< 40 amu) from the Giotto mission's high-speed exploration of Halley's comet (Geiss et al., 1991; Haider & Bhardwaj, 2005). However, results from the Cassini Ion Neutral Mass Spectrometer (INMS) revealed that sampled material travelling at high velocities may have significant physical and chemical interactions with the instrument. High-velocity sampled material actively damaged the chamber's walls, releasing titanium and promoting the chemical absorption of organics such as benzene by the instrument (Jaramillo-Botero et al., 2012). Thus, the mass spectrometer's surface reactivity and the resulting chemical reactions may further complicate the interpretation of possible organic matter. Additional development work would likely be required to understand these effects in the context of a 70 km/s ISO encounter.

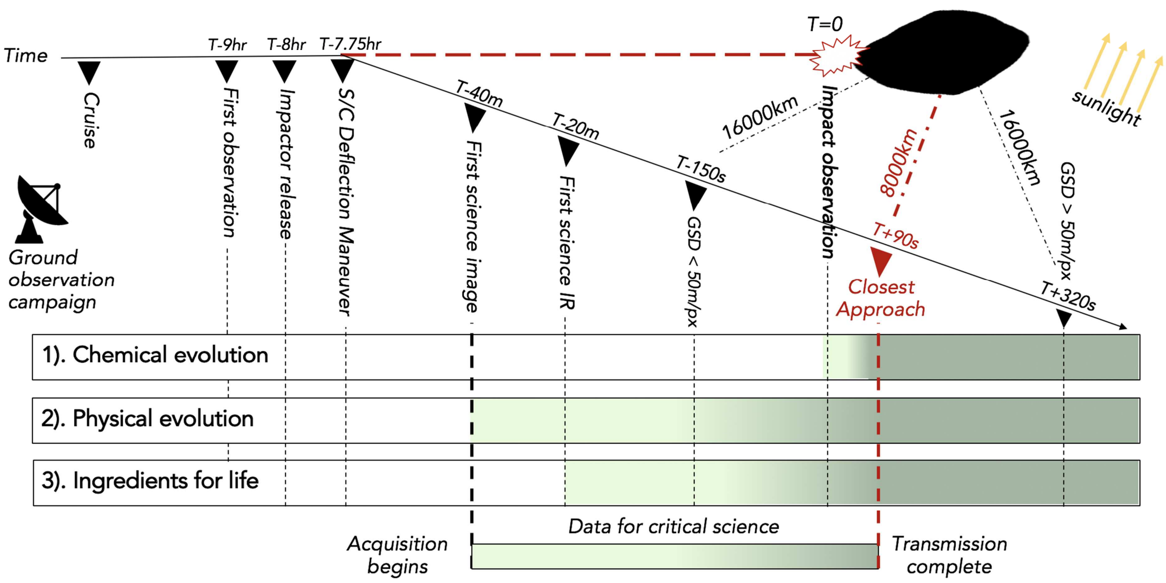
We decided against mass spectrometry primarily due to the uncertainty in the availability of dust and gas that can be sampled without incurring risk to the spacecraft. We have designed Bridge with sufficient flexibility to encounter a generic ISO; while volatile-rich ISOs may be actively outgassing (Bannister et al, 2019; Guzik et al, 2019), this is not guaranteed for ISOs that may be rockier in nature. While Bridge's impactor would generate an ejecta that could potentially be sampled by a mass spectrometer (including material from the object's interior), collecting this ejecta material would impose a substantial risk by requiring mission-critical measurements to happen



post-impact.

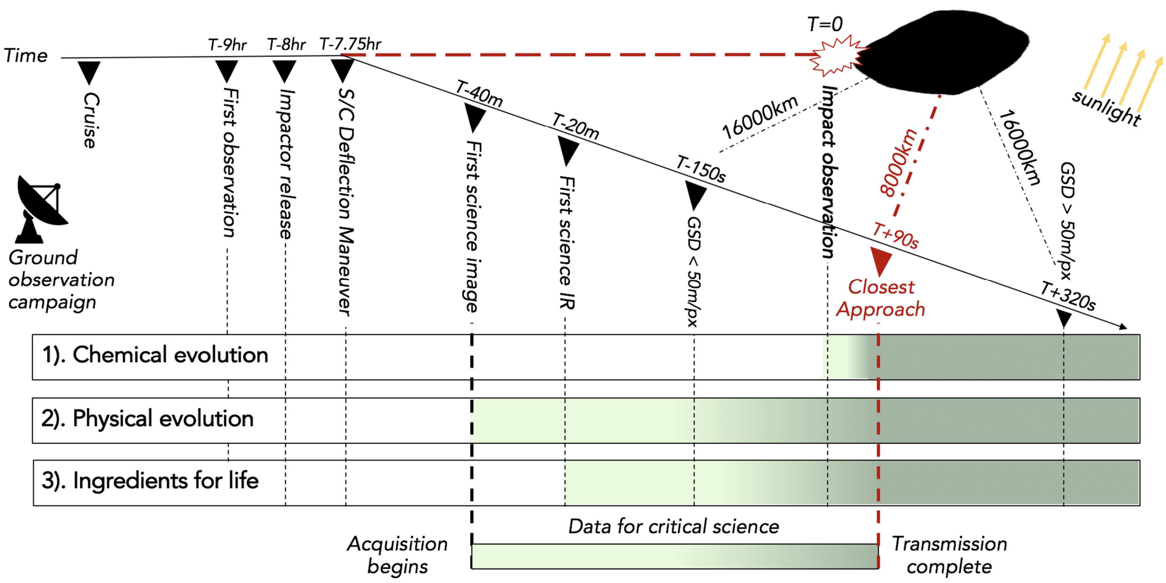
Even assuming that there is material present to sample, collecting it would require Bridge to encounter the ISO in close proximity, perhaps at a distance of 10s-100s of km. At the high velocity expected for the flyby, any large dust particles from the object could be hazardous to the spacecraft. For example, the Giotto mission was destabilized by a strike with a 0.1-1g dust particle just seconds before its 600 km closest approach to the Comet Halley nucleus, while travelling at a relative speed of 68 km/s. Multiple instruments were damaged during the flyby, and the spacecraft's angular momentum vector was deflected by 0.9 degrees. Giotto's communications were intermittent for over thirty minutes afterward (Reinhard, 1986). The possibility of high-velocity dust impacts during sample collection would have added substantial risks to Bridge, especially given our narrow window for data collection.

In summary, we felt that the risks of obtaining in situ samples from an unknown environment as well as the potentially limited ability to identify individual organic compounds outweighed the benefits of a mass spectrometer for our mission concept. Instead, we chose a remote sensing payload that meets our science objectives while allowing for a safe observing distance of up to 8000 km. This distance would allow for relatively safe continuous science observations (decreasing the risk of dust impacts from a possible coma), assuming a maximum relative velocity at close approach of 70km/s and capping the maximum slew rate 0.5°/sec to minimize image smear. Future work may help to enable in situ sampling of ISOs by providing more constraints on



the dust and outgassing environment of interstellar objects to ensure a safe flyby for close sampling, as well as continued development research on in situ sampling technology at high velocities.

In addition to our trade of mass spectrometers versus a remote sensing instrument payload, we also opted for point spectrometers over imaging spectrometers. To mitigate risk, we desire all critical science data to be downlinked to Earth before closest approach. Spatially resolving the ISO while addressing our science objectives would require high spectral resolution and fast frame rates, leading to a sizable volume of data per pixel and significant instrument mass. However, our science objectives only require spectrally identifying the *presence* of key elemental and molecular species on and within the target body, and not their spatial variation. Thus, we consider only single-pixel point spectrometers, which dramatically reduce the data volume to be downlinked when compared to imaging spectrometers (a 2D array of pixels). Without a spatial axis, point spectrometers are also simpler and lighter instruments that can accommodate the extra mass associated with our required spectral resolution, as well as a deep sensor well to enable higher SNR over imaging spectrometers. We also require fast readouts times of 20 Hz for our all instruments in order to fully characterize, both chemically and physically, the rapidly evolving plume generated by our impactor. Fast readout times require that an instrument rapidly commit data to memory, similarly increasing power needs. Using point spectrometers over imaging spectrometers greatly alleviates memory and power demands, mak



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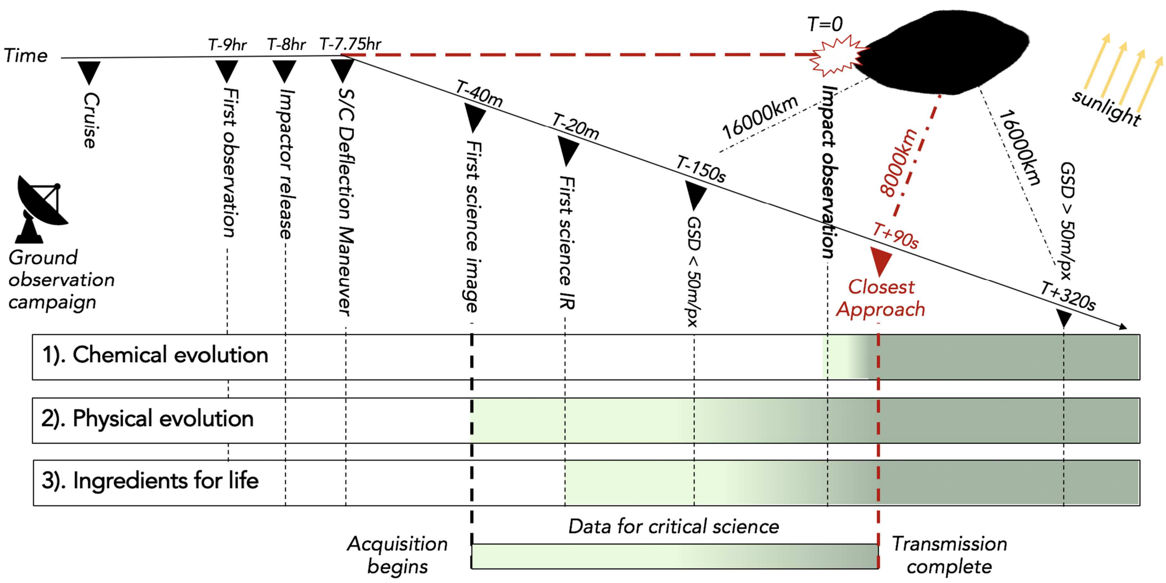
uisition feasible. Additionally, we would plan to make rapid measurements following the initial impact event and leading into the outbound phase of our flyby, a sequence of events that would take place over the course of only a few minutes. However, if needed, adding additional memory to our instruments is not unrealistic. Thus, we find point spectrometers to be ideal to meet the science requirements and technological and cost constraints of an ISO encounter.

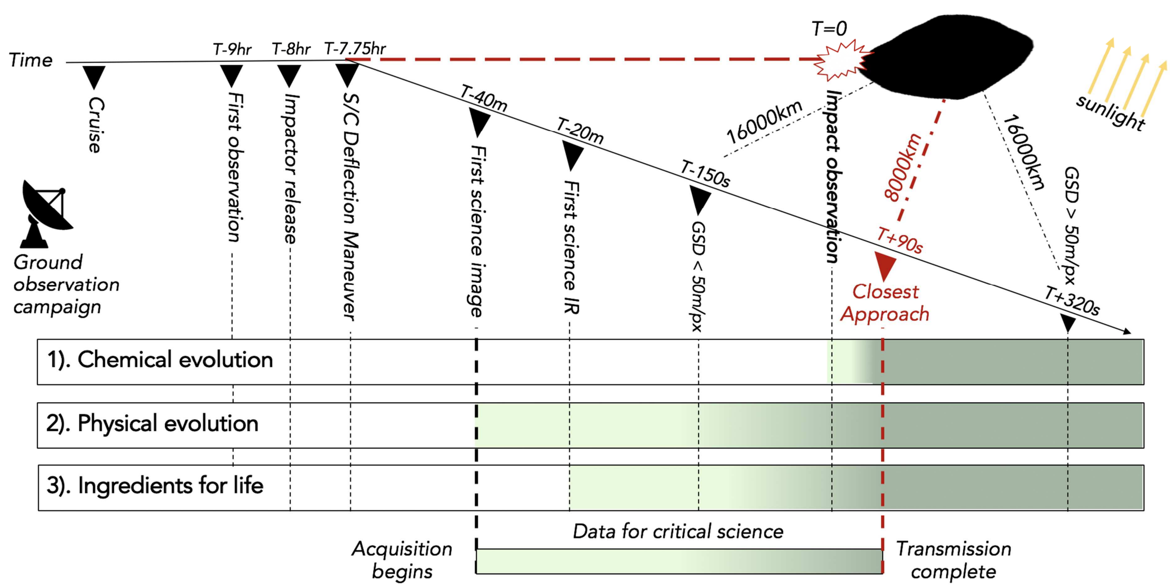
Finally, Bridge would use a kinetic impactor to excavate fresh material from an ISO's interior. This is necessary since the surface may have experienced significant radiation hardening during its voyage through interstellar space (Seligman & Laughlin 2018, Vavilov & Medvedev 2019). There are two main types of impactors to choose from: passive and active impactors. A passive impactor is essentially an inert mass of metal that is set onto a ballistic collision course with a target (e.g., the Hayabusa2 Small Carry-On Impactor; see Saiki et al., 2013), whereas an active impactor is a miniature spacecraft that contains a guidance system (propulsion, attitude control, cameras, etc.) that can actively impact a target in the face of uncertainty (e.g., the Deep Impact Impactor; see A'Hearn et al., 2005). We choose an active impactor for Bridge because the uncertainty of a passive impactor's trajectory would preclude a guarantee of impact. The nominal requirement of Bridge's impactor is to intercept an ISO of similar size or larger to 1I/'Oumuamua at a relative velocity of 70 km/s. A passive impactor would require extremely accurate knowledge of the spacecraft and ISO's position and velocity to guarantee a hit. Considering the scenario discussed in Section 4.2, at the time of impactor release, the ISO would be



approximately 2,000,000 km away from the spacecraft. With a 0.3 mrad pointing accuracy (technical specification of the HR12 Honeywell reaction wheels), the impactor would have a final position uncertainty of approximately 600 km. Additionally, the uncertainty in an ISO's state can vary wildly depending on the number of observations used to determine its orbit. For example, even after 207 observations, there is still a 45,000 km three-sigma uncertainty on 1I/'Oumuamua's semi-major axis and additional three-sigma uncertainty on the other orbital elements on the order of 0.01° (JPL Small-Body Database, 2019). These uncertainties can result in position differences as large as 70,000 km at the point of interception. While observations from the Bridge spacecraft would shrink the uncertainty in the ISO's trajectory, uncertainty of this magnitude still necessitates an active impactor to guarantee a collision with an ISO.

6.1.2 Trajectory Trade Space & Power System Implications

We design Bridge to fly under specific criteria: an inner solar system intercept between 0.7-2AU, target detection up to two years before the ISO's perihelion, and a six-month turnaround time from detection to launch. Adopting these criteria offers multiple benefits. For example, intercepting the target in the inner solar system requires only a few months of flight time, reduces data downlink and thermal requirements compared to an outer solar system flyby, and the large amount of sunlight allows for the use of solar power. However, inner solar system intercepts also require



early ISO detection, adequate positioning of Earth relative to the inbound ISO, and generally leads to spacecraft trajectories laying close to the ecliptic plane.

How important are each of our individual launch criteria? For example, could long duration outer solar system chase trajectories enabled by radioisotope power systems enable lower velocity encounters and in situ sampling? How critical is the six-month detection to launch turnaround time? Which launch criteria are essential to ensuring mission success (i.e. a suitable ISO is discovered /within our allotted 7-year storage window) versus which criteria are unnecessary burdens? These are questions that not only influence our mission concept's design, but provide important planning information to the planetary science community more broadly.

In order to evaluate these questions, we perform a Monte Carlo analysis. The primary goal of this analysis is to provide a trade study for inner solar system intercept missions to the community, and explain the factors that influenced our design choices. With this in mind, we emphasize that our focus is to perform a relative analysis of which launch requirements are most enabling or prohibitive to mission success, rather than the exact percentage of ISOs that can be reached with our specific spacecraft point configuration. Thus, we make several simplifying assumptions to reduce our computational burden, which are described below.

In particular, most of our models assume that incoming ISOs have a Gaussian distribution about the Solar Apex (see Appendix B for more details). While this assumption gen erall y alig ns with

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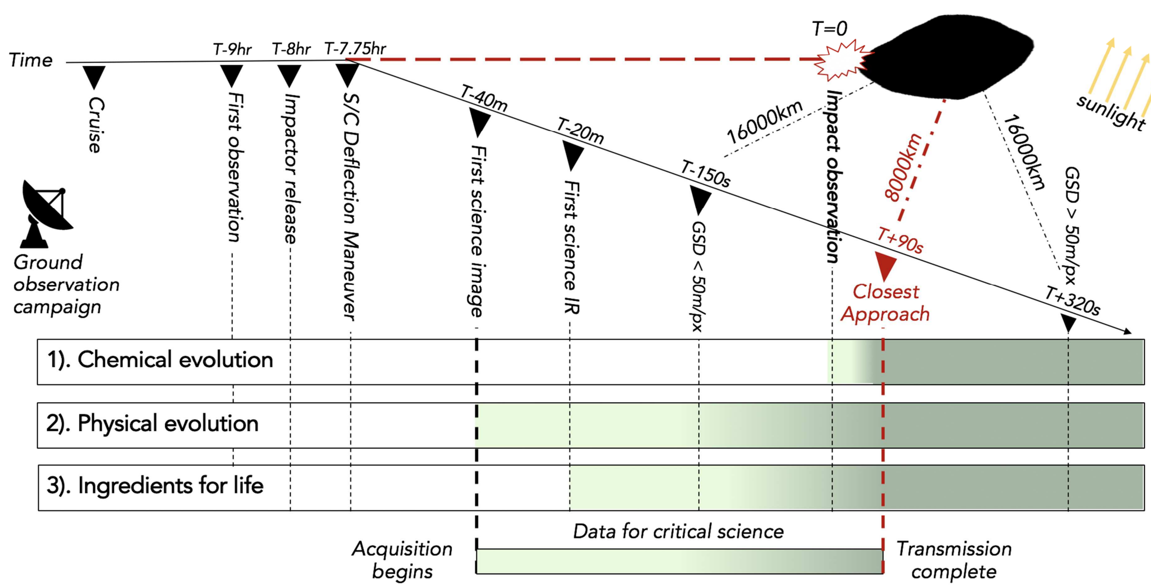

the most probable source region of ISOs, our implementation is significantly simplified compared to state-of-the-art models in the literature (Cook et al., 2016; Seligman & Laughlin, 2018). Such models perform a more precise accounting of the galactic distribution of ISOs (e.g. Do et al., 2018) by including the locations of individual source stars in the local stellar neighborhood, as well as the dynamical scattering effects of different stellar populations (see Binney & Tremaine, 2008). However, we find that incorporating the full complexity of the statistical distribution of ISOs is unnecessary for the purposes of our mission trade analysis. Even drastically changing the probability of incoming ISOs by assuming it is completely isotropic across the full sky, we find that the resulting successful encounter rates do not change significantly (< 1% difference). This effect is significantly smaller than the effect of adopting different sets of launch criteria, suggesting that our assumptions still yield sufficiently accurate analysis for evaluating our trade study options. A more rigorous analysis incorporating the full statistical distribution and detectability of ISOs coupled with trajectory analysis is beyond the scope of our study, but would be appropriate for a future work or formal mission proposal.

For our baseline case, we calculate the percentage of ISOs that Bridge could reach under the launch criteria outlined in Section 4. In this case, the spacecraft successfully reaches 6,502 of our simulated 10,000 ISOs. This gives a single ISO successful encounter percentage of 65.02%, i.e. for any given ISO that is discovered, there is a 65.02% chance that Bridge could reach it (we emphasize that Bridge would only launch after trajectory calculations determined it

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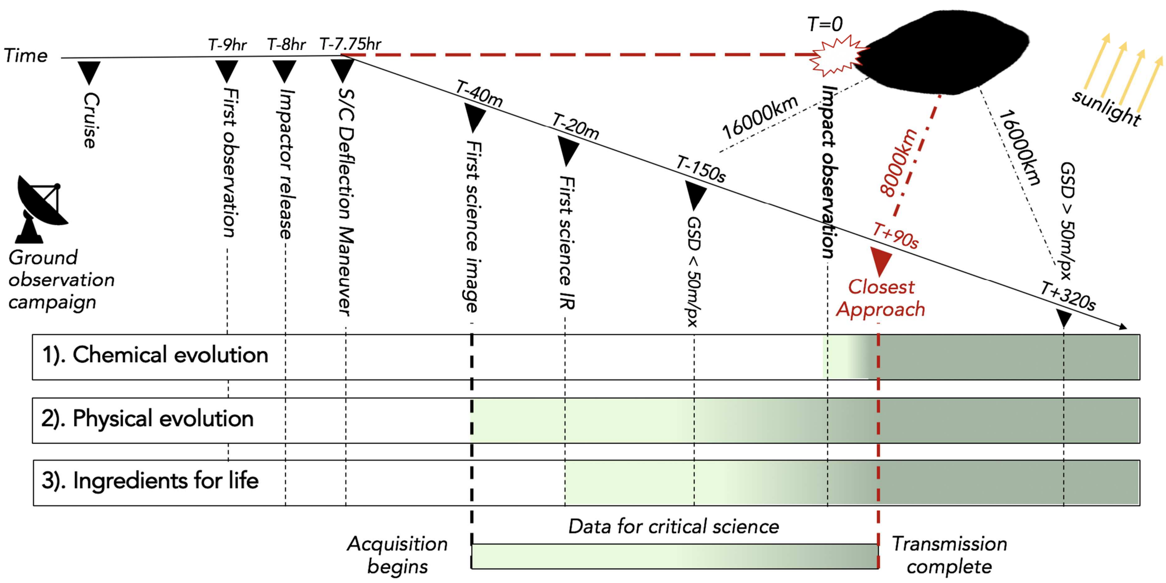
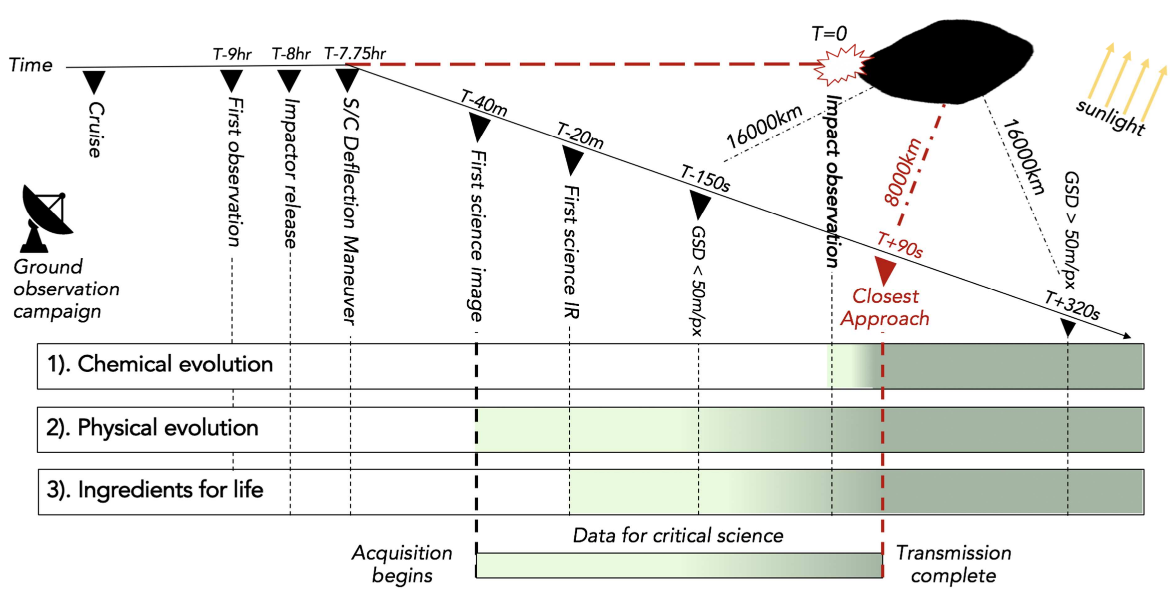
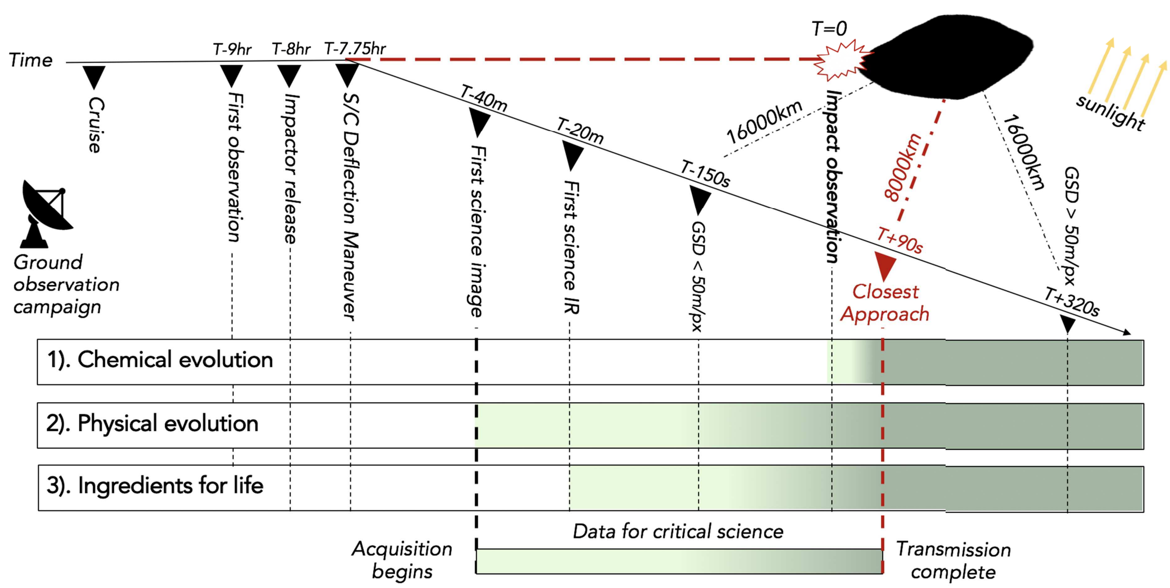


cific ISO). While not every ISO would be reachable, we have budgeted for up to seven years of long-term spacecraft storage on the ground. After calculating the percent of incoming ISOs that are reachable ("single ISO reachability rate"), we scale this value by the predicted flux of detectable, incoming ISOs. Specifically, we assume up to one potential ISO detection meeting our assumed population model per year based on the capabilities of next-generation survey telescopes such as the Vera C. Rubin Observatory (Trilling et al., 2017a; 2017b); while the exact flux of incoming ISOs is still a matter of scientific debate, our analysis represents a reasonable extension of current projections available in the literature. Thus, our calculated cumulative probability of discovering an ISO that Bridge could reach is the probability of at least one out of seven ISOs meeting the launch criteria. For our nominal spacecraft which can successfully encounter 65% of inner solar system ISOs, this gives a seven ISO mission encounter probability of 99.94% (see Table 5).

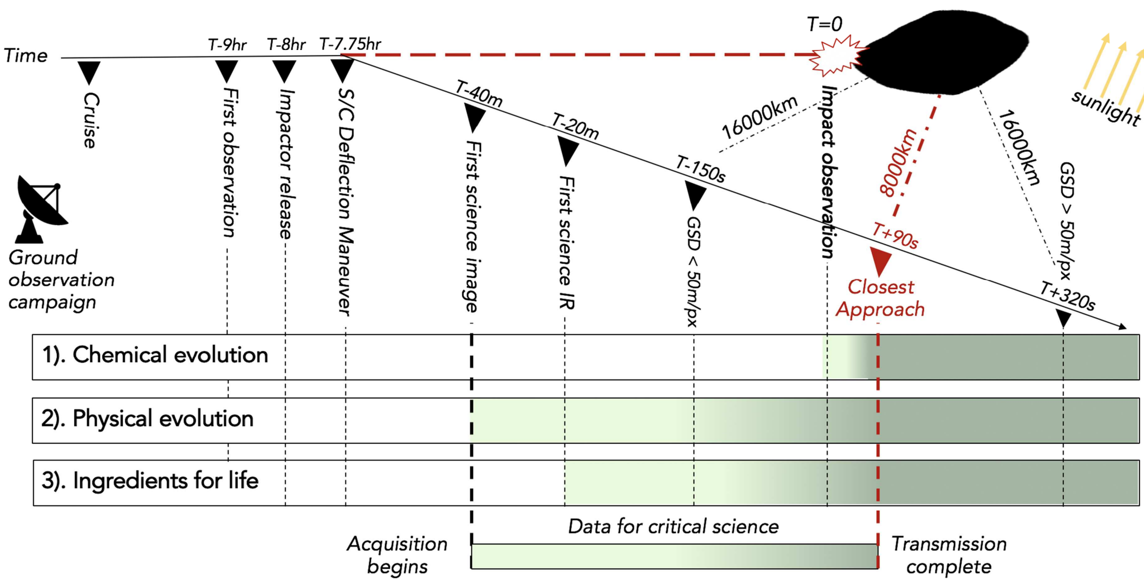




Solar apex	Full sky	Solar apex
< 70	< 70	
2	2	0.25
180	180	180
0.7-30	0.7-30	0.7-30

Table 5 shows the effect of relaxing or strengthening different launch criteria: the encounter distance, relative encounter velocity, detection window, launch turnaround time, and spacecraft size. One of the strongest constraints is the relative encounter velocity. Unfortunately, we find that limiting a spacecraft to even a relative encounter velocity of 40km/s reduces the percent of reachable ISOs to 69.34% over seven years. While it's possible that an individual ISO may be discovered which would allow for a slow encounter speed, our analysis suggests that the percentage of ISOs with such a favorable trajectory is low. In contrast, our upper bound on relative encounter speeds of 70 km/s appears to be sufficient, since increasing it to 100 km/s does not enable significantly higher success rates.

We also considered the effect of detection and launch turnaround time. Our study assumes a nominal detection window opening two years before perihelion. How reasonable this is depends on the physical properties of incoming ISOs as well as observatory capabilities. The majority of ISOs are predicted to be icy, cometary objects, similar to 2I/Borisov (Fitzsimmons et al., 2018). Of the bodies in our solar system, they would hypothetically be most comparable to Oort Cloud comets; these are "fresh" comets that have retained most of their volatile inventory, and so are some of the brightest comets in the sky. Reinforcing this point, 2I/Borisov was bright enough to be discovered with a 0.65m telescope (Guzik et al., 2019). PANSTARRS has routinely discovered Oort Cloud comets such as comets C/2011 L4 (MPEC, 2011), and C/2017 (MPEC, 2017) 2-5 years before perihelion, in line with our two-year detection window ass



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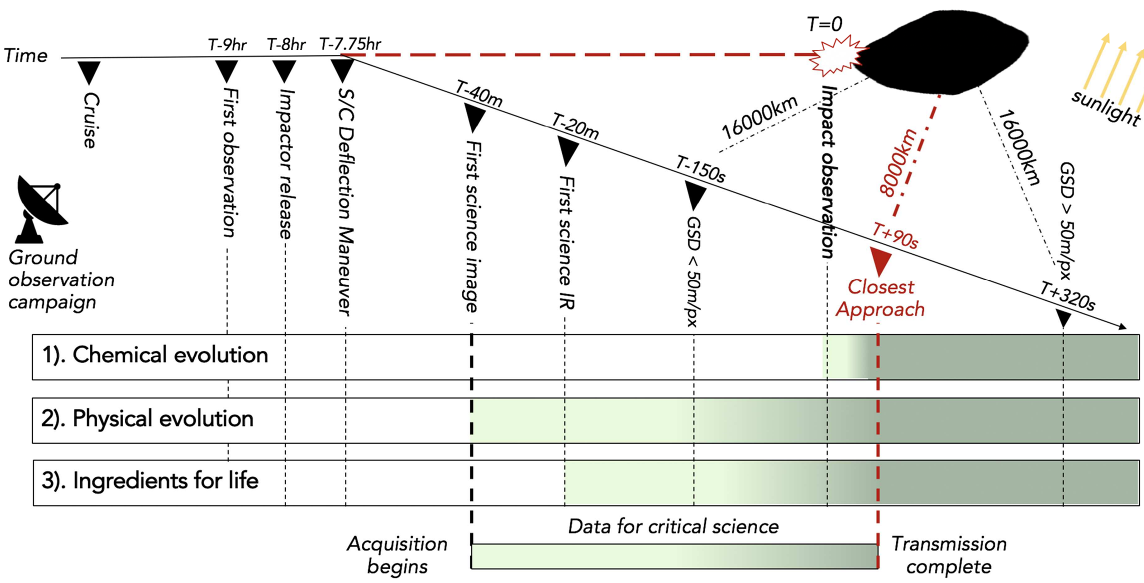
etary ISOs will likely be travelling faster than Oort Cloud Comets (and therefore would have shorter detection windows), the upcoming Vera C. Rubin Observatory will also have higher resolution than PANSTARRS. Thus, our two-year detection window is plausible for icy ISOs of a certain size threshold, assuming next-generation telescopic capabilities.

We have also included additional cases in our trade study using shorter detection windows (one year or three months before perihelion) which would be more applicable to smaller, rocky, or radiation-hardened ISOs similar to 1I/'Oumuamua. As the detection window decreases, the single ISO encounter rate drops sharply from 65.02% to 22.11% (one year before perihelion) or 0.00% (three months before perihelion), making the mission significantly less feasible. These results emphasize the need for NASA to invest in advanced ground telescope capabilities and to make these resources available to the planetary science community. The penalties imposed by a reduced detection rate could be partially offset by other advances such as rapid launch capabilities (e.g. implementing a 90 day launch delay rather than a six month delay or allowing the spacecraft to remain in storage for even longer periods of time. We note that even a "low" single ISO reachability rate of 33% (for a one-year detection window and a 90 day launch turnaround time) still gives a much higher total mission encounter rate of 94.31%, which may be sufficient.

Additionally, we investigate the effect of encounter distance. Our original criteria require Bridge to encounter the ISO in the inner solar system between 0.7 and 2.0 AU. We find that rela



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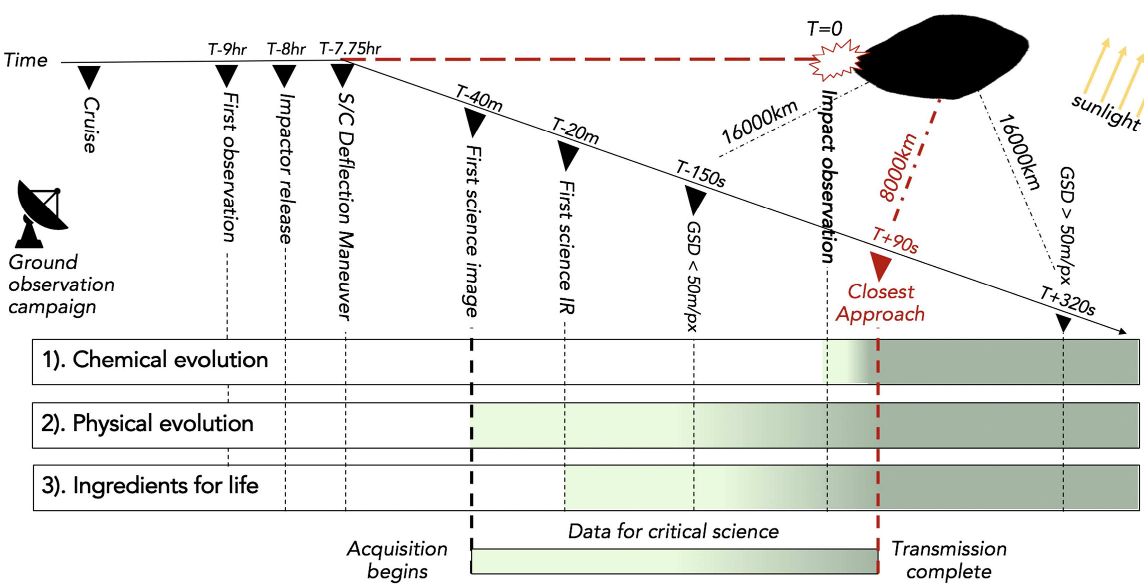
to 0.1 to 3.0 AU only mildly improves the percent of ISOs that Bridge can reach (from 65.02% to 69.87%), and has almost no effect on the total reachability of ISOs over the mission's seven years.

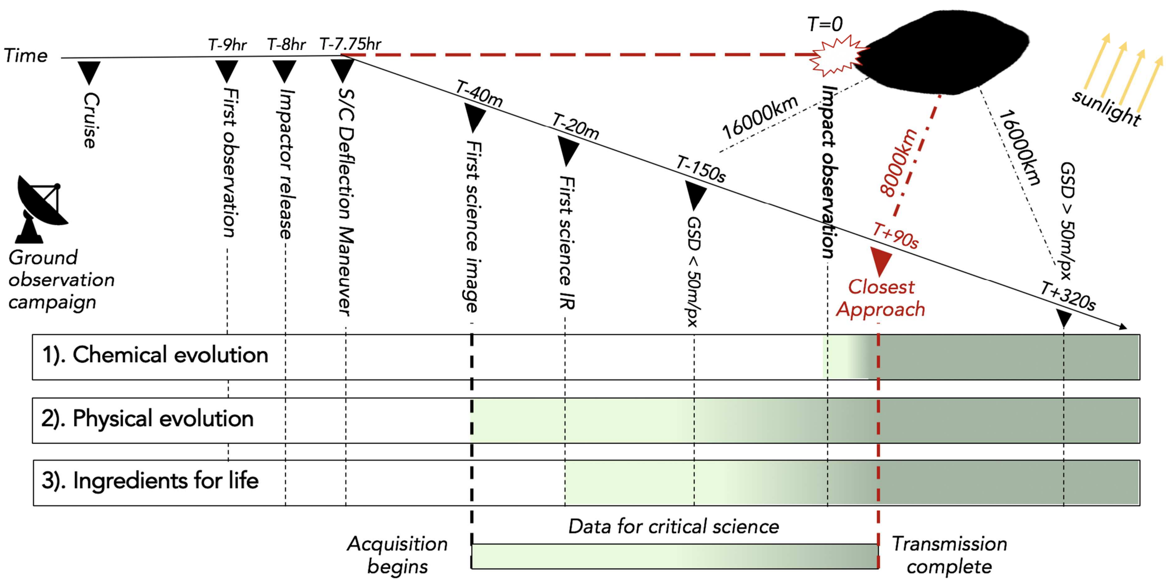
Further afield, we consider outer solar system encounters. Compared to intercepts in the inner solar system, outer solar system intercepts have both advantages and disadvantages. These outer solar system encounters are generally lower in relative velocity, but occur far from the Sun and Earth. Thus, these missions receive less sunlight, reducing data transmission rates and SNR. These missions would also face significant challenges in terms of power (this trade is described in more detail later in this Section). Importantly, an outer solar system intercept also does not guarantee a significantly lower relative velocity at intercept. Note that our outer solar system trajectories do not incorporate potential gravity assists from the massive outer planets Jupiter and Saturn, and represent only the statistics of direct launches from Earth.

Overall, our study finds that a small, New Horizons-class spacecraft traveling to the outer solar system has the highest chance of reaching any individual ISO out of all cases studied (85.88%). However, this is almost entirely due to the halved spacecraft mass, which enables a higher launch C3. (*C3, or characteristic energy, is a measure of the excess energy upon departure from Earth, formally defined as the square of the departure relative velocity,* V_{∞}^{2}. *Note that this is double the specific orbital energy)*. A new Horizons-class spacecraft restricted to the inner solar syst



em raises the percent of single reachable ISOs from 65.02% to 82.52%; expanding the encounter range to the outer solar system only yields an additional 3% of reachable single ISOs (up to 85.88%). We also find that for severely late detections only shortly before perihelion, an outer solar system encounter is likely the only way to reach an ISO; the single ISO reachability rate of an inner solar system mission with a three month detection window and an immediate launch upon detection is only 6.11%. However, even an outer solar system encounter with a significantly lightened (New Horizons-style) spacecraft can still only reach 17.88% of our simulated ISOs, for a total mission encounter probability of 74.81%. Thus, an outer solar system mission only provides a 75% threshold for reaching an ISO after seven years in storage, emphasizing again the importance of making advanced detection capabilities available to the planetary science community.

Because our Monte Carlo analysis provides an estimate of the success rate for inner and outer solar system encounters, we are able to analyze the trade between an RTG and solar powered ISO mission. RTGs are not required for an inner solar system encounter, as 10 m solar panels would provide sufficient power even at the farthest encounter distance of 2 AU. However, for encounters in the outer solar system, radioisotope power would be a key enabling technology, required due to the reduced sunlight conditions. However, we note that outer solar system flight times are on the order of a decade or more (see the Hein et al.[2018] and Hibberd et al. [2019] mission designs), which may test the performance limits of current RTG power systems -- especially if



multiple additional years were required to find a suitable ISO target before launch. Because allowing outer solar system encounters does not significantly improve the chances of a successful encounter, we find that RTGs are not a necessary power source for Bridge.

Our Monte Carlo analysis provides a trade study for planning a potential mission to an ISO, and also provides a first-order estimate of the feasibility of such a mission. A more precise analysis including the full kinematic distribution, number density, and detectability of ISOs is beyond the scope of this mission architecture study. Further, we emphasize that although ISOs have been the subject of extensive theoretical analysis in the literature, only two ISOs have been definitively detected so far. Thus, there is extensive uncertainty in their physical and orbital properties and arrival rates. As more ISOs are discovered, our estimates of Bridge's feasibility may prove optimistic or pessimistic.

6.1.3 Ground storage vs parking orbit

Due to the fact that Bridge is a mission of opportunity (i.e., the mission only begins with an ISO detection), the Bridge spacecraft was designed to be stored on Earth in a cleanroom environment such as the JPL High Bay until a suitable ISO target is detected. Under this scheme, once a target ISO is identified, Bridge is removed from the cleanroom, transported to the launch pad, affixed to a launch vehicle, and finally launched directly from Earth onto an intercept trajectory with the ISO. This approach contrasts with the concept proposed by the

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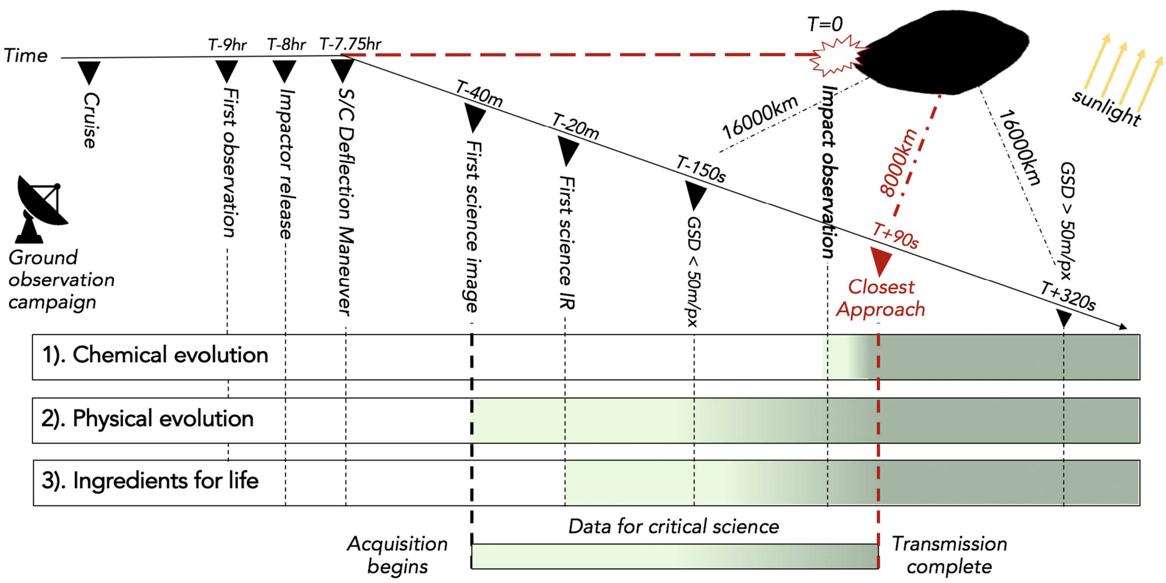
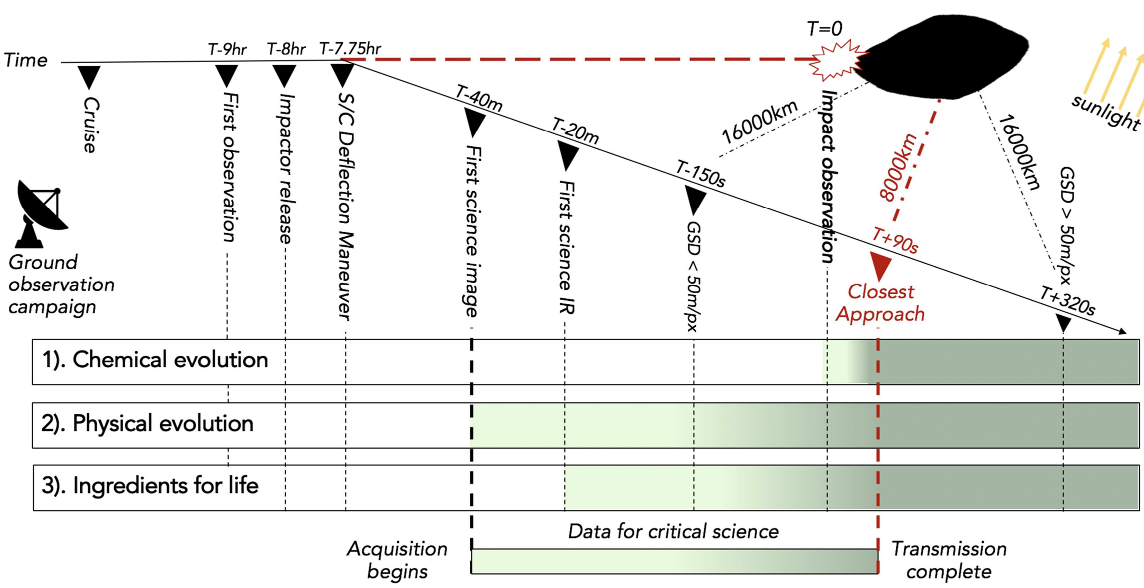


m (Jones 2019) and Seligman and Laughlin (2018), who advocate for launching the spacecraft plus an attached solid rocket motor into a parking orbit, such as the L2 Sun-Earth Lagrange point, and waiting in orbit until a suitable ISO is discovered. Once a target ISO is detected, the spacecraft would perform a final maneuver using the solid rocket motor (SRM) to enter an intercept trajectory with the ISO.

Using a combination of orbital mechanics, the Tsiolkovsky rocket equation, and the 1I/‘Oumuamua intercept trajectory shown in Figure 4 as an example, we compare the two mission strategies. For the sake of this comparison, it is assumed that the Bridge spacecraft starts in a circular 185 km LEO parking orbit and uses a single-engine Centaur upper stage. When looking at the ground storage option, the Bridge spacecraft needs a hyperbolic excess velocity of 4.456 km/s to intercept the ISO, which corresponds to a 4.1 km/s maneuver from the LEO parking orbit using the Centaur. In contrast, to intercept the same ISO, Bridge would need to perform a 3.43 km/s maneuver from the Sun-Earth L2 Lagrange point using an approximately 2500 kg SRM (when assuming a thrust of 200 kN and a specific impulse of 285 seconds for the SRM), which requires an additional 3.23 km/s maneuver from the 185 km LEO parking orbit just to reach L2. These two maneuvers result in a total of maneuver cost of 6.66 km/s vs the 4.1 km/s cost of the ground storage option. These results, along with the associated fuel costs, are summarized in Table 6.

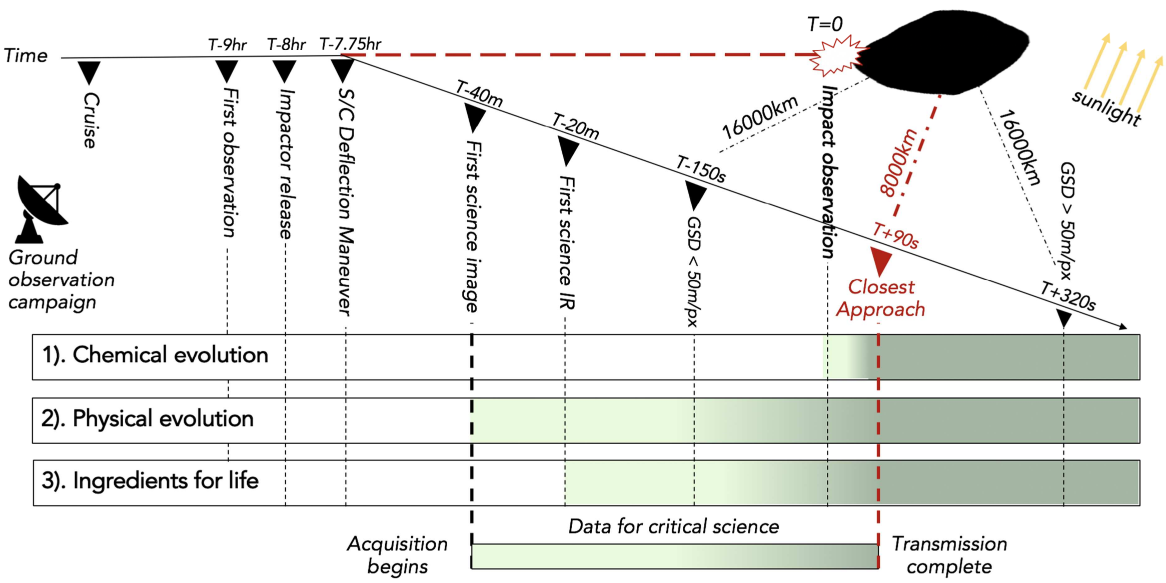
While both storage methods are feasible, the ground storage option has the profound benefits of spacecraft



safety and mission simplicity. In regards to safety, storing an SRM in space is an additional point of failure, whereas a cleanroom environment is ideal for spacecraft storage. If the SRM fails to ignite, then the mission would fail. Additionally, a direct launch from Earth to an ISO intercept trajectory requires fewer spacecraft maneuvers, less overall fuel, and allows Bridge to minimize launch mass and maximize the delta-v obtained from the launch vehicle. Furthermore, the fuel savings of ground storage would allow Bridge to reach more potential ISOs than if the spacecraft were stored in space, which ultimately reduces the expected wait time to find a suitable ISO. For the combination of these reasons, we advocate for ground storage. However, ground storage also has surmountable drawbacks such as reduced response time and rapid launch capabilities. This is largely a programmatic and logistical challenge that has already been overcome by defense-oriented launches and is more thoroughly discussed in Section 6.2.2.

Table 6: Comparison between fuel costs of a parking orbit and ground storage of the Bridge spacecraft

Method	ISO intercept maneuver (km/s)	Fuel (kg)	Launch to L2 maneuver velocity (km/s)	Fuel (kg)	Total fuel (kg)
L2 parking orbit	3.43	2388	3.23	6055	8443



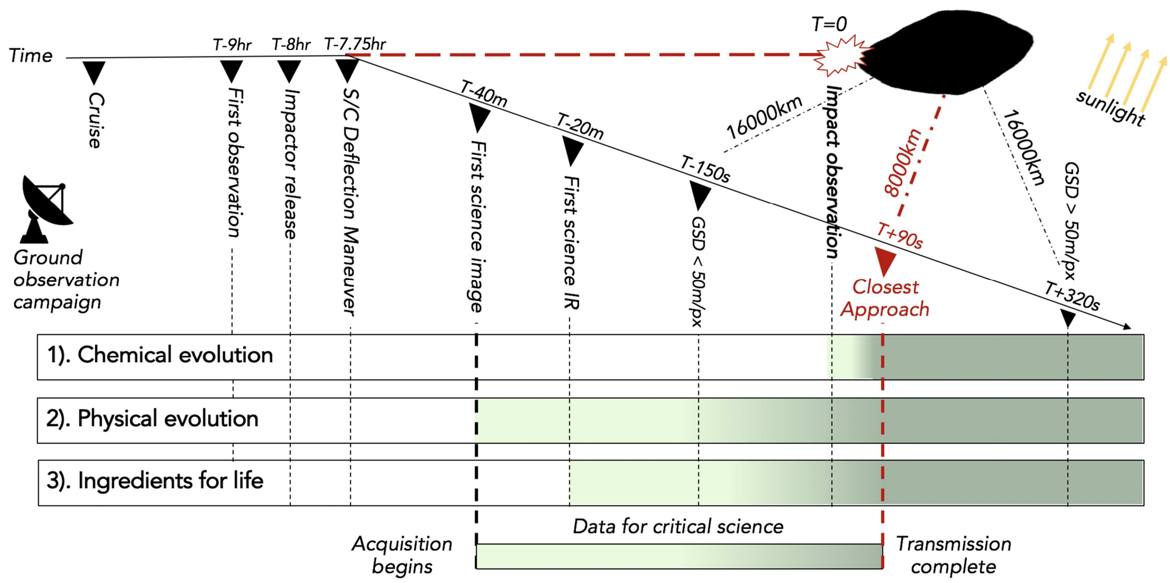
Ground storage	4.10	4791			4791

6.2 Enabling technologies & policies

To enable our mission concept, several technological advancements and policy changes need to occur. This includes: improved ground detection capabilities of small bodies, additional instrument development, infrastructure to store a completed spacecraft in a launch-ready state, rapid launch response, and the opportunity to propose a mission that requires these capabilities. All of these items should be feasible in the immediate future, given a few specific programmatic and technological developments.

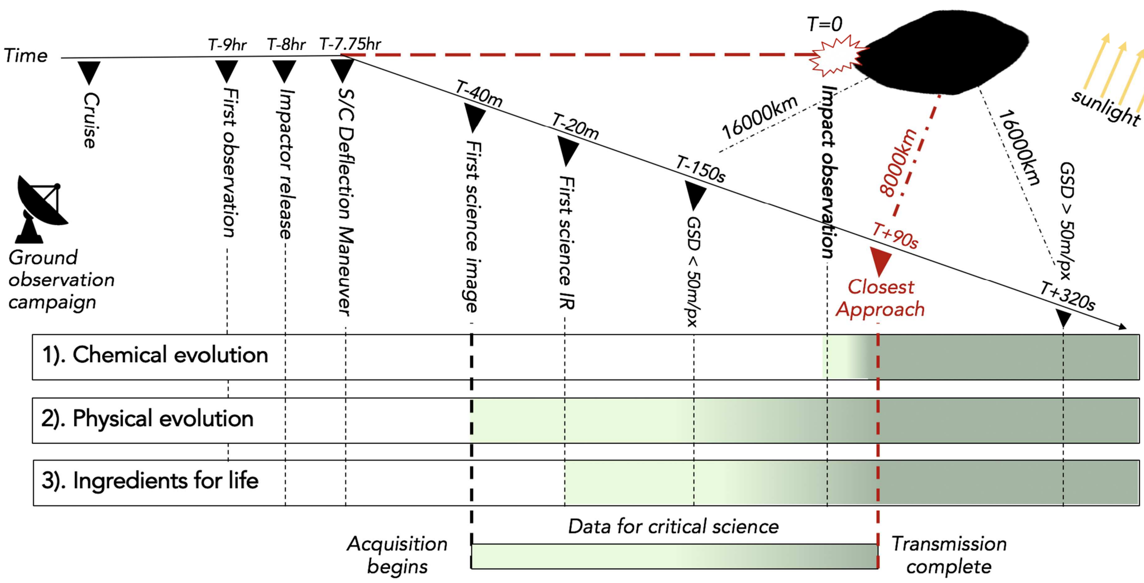
6.2.1 Instrument development

The conceptual design of the UV-VIS instrument builds on optics and sensors flown on the Trace Gas Orbiter (TGO)'s UVIS-NOMAD instrument (Robert et al., 2016), the MAVEN mission IUVS (McClintock et al., 2015), and New Horizons' ALICE (Stern et al., 2009) but with wider spectral range, larger aperture, and a narrower field of view. We argue for the inclusion of an echelle channel in order to quantify the ratio of ^{16}O to ^{18}O, a measurement critical to achieving science obje



ctive 1. An echelle channel, as specified in Section 3.4, would provide the necessary resolving power (concentrated in a small spectral range) to distinguish key emission lines otherwise inaccessible to the wide-spectrum sensor. In particular, including a beam splitter would enable the simultaneous operation of the echelle channel and the wide-spectrum sensor. An optical demultiplexer, such as that used aboard the Mars Science Laboratory's ChemCam (Wiens et al., 2012), utilizes a dichroic beam splitter arrangement that can provide almost twice as much in-band light to both the standard and echelle UV channels when compared to a simpler neutral-density beam splitter arrangement, thus avoiding the dilution of measurable light that can come with using a standard beam splitter.

Existing sensors would also need to be upgraded to support single pixel rather than multi-pixel imaging measurements. Linear sensors with the desired spectral range and spectral resolution are commercially available from Ocean Insight (e.g., OCEAN FX-UV-VIS point spectrometer), but need to be qualified for space flight. A similar development path was taken for the UV-Visible point spectrometer included aboard LCROSS, which used a modified-commercial QE655000 model from Ocean Insight (Ennico et al., 2010). Development funds would need to be allocated to the UV-VIS spectrometer to bring the conceptual design to maturity and qualify the whole instrument for space flight. We have accounted for this by explicitly budgeting for these development costs in our Team X study; however, while these were costed as a "minor modification", it is possible that development costs could be substantially higher. We

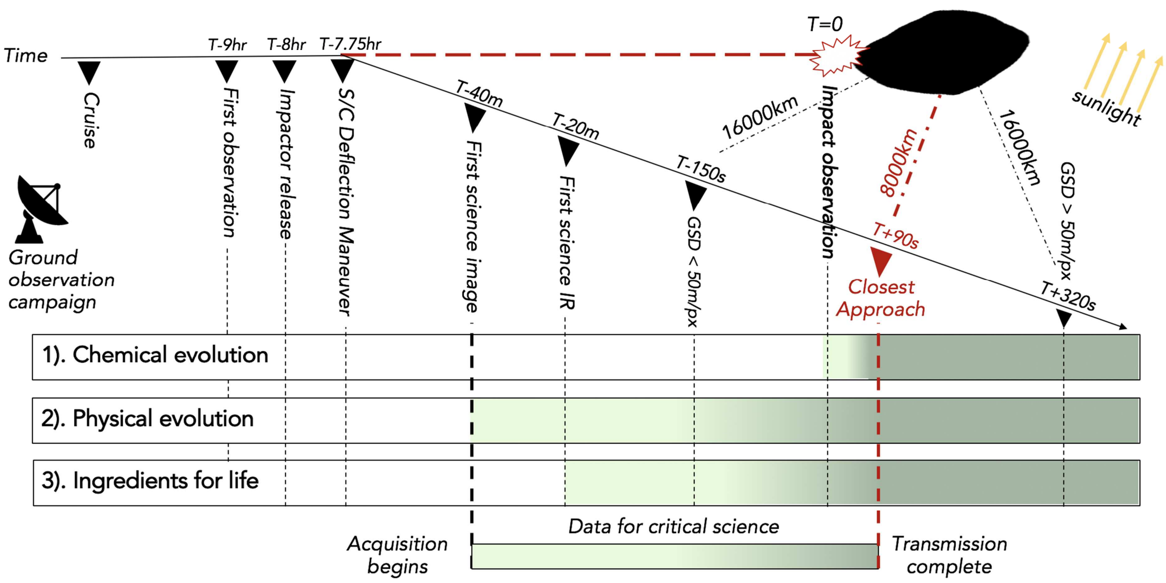


note that the mission concept provides significant reserves to accommodate cost risks such as this.

Similarly, development funds would also need to be allocated to the mid-IR instrument to bring our point spectrometer concept to maturity. The current concept for the instrument is to combine forward optics based on previously flown missions with a commercially available sensor such as the Ocean Insight MZ5 ATR-MIR Spectrometer. Development work would need to be carried out, likely in partnership with commercial entities, to qualify the entire instrument, including the commercial sensor, for flight. This activity would leverage previous qualification of Ocean Insight spectrometers (e.g. Ennico et al., 2010; Saccoccio et al., 2009) for use in space missions.

6.2.2 NASA New Frontiers AO changes: Storage & launch

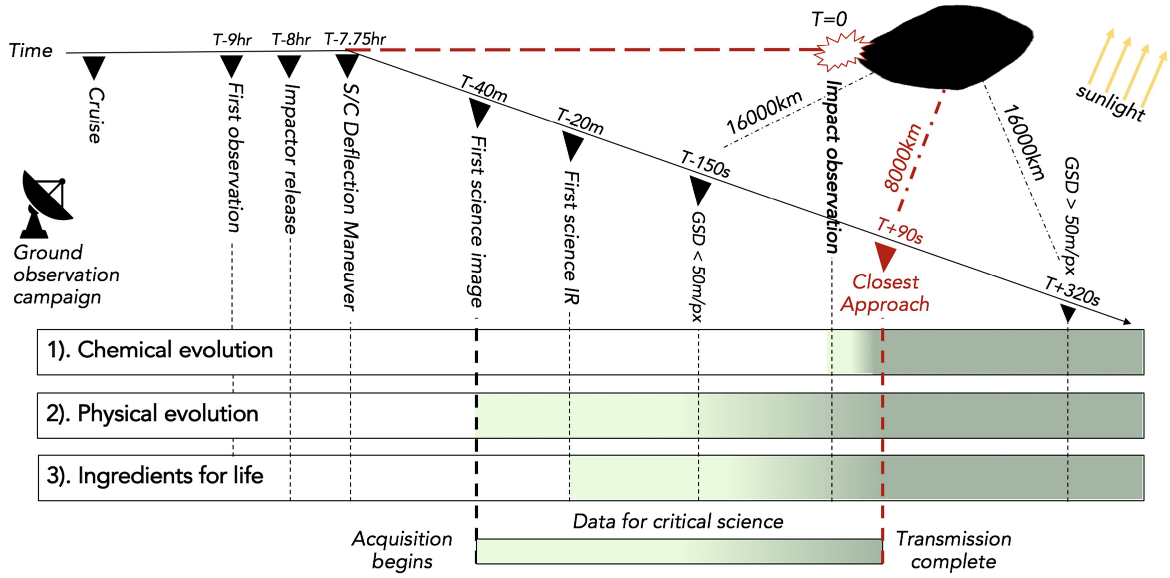
We design Bridge to wait in ground storage until a suitable ISO target is discovered. We explicitly budget for seven years of ground storage. Spacecraft storage is not uncommon, and obstacles like instrument development delays and political climates have previously forced spacecraft into extended clean room storage. For example, NASA's InSight spacecraft spent over two years in clean room storage after a launch window was missed due to an instrument delay (NASA, 2015). Despite spacecraft storage being common, under current NASA AO guidelines, it is not permitted to propose a spacecraft that explicitly requires ground storage (NASA 2016). If NASA



would like to consider a mission like Bridge to reach an ISO in the future, we recommend revising the language of the next New Frontiers AO (and other similar AOs such as SIMPLEx or Discovery) to explicitly allow for pre-planned spacecraft storage over an extended time period.

In addition to requiring storage, the quicker Bridge can transition from storage to launch, the quicker it can encounter a target, increasing the number of ISOs it could potentially reach (see Table 5). Our mission is designed to have a combined turnaround time from observation to launch of 6 months. At the time of this writing, the Mars 2020 rover is in transport to Cape Canaveral with an expected launch date within 6 months (NASA, 2020). We assume that the project could transition Bridge from storage to launch at Kennedy Space Center in a similar time period.

To transition a spacecraft from storage to launch within a limited time frame, a launch vehicle must have been pre-purchased with a flexible launch date. Rapid and flexible launch capabilities are a standard procedure for the U.S. military, so this is a programmatic hurdle and not a technological one. The continuing growth of commercial launch vehicle companies, which plan to achieve launch cadences of dozens per year within the decade (Reddy, 2018), would also mitigate this issue by making a flexible launch schedule easier to accommodate. Thus, to enable Bridge, the planetary science community must consider advocating for language in the New Frontiers AO that explicitly allows for purchasing a launch vehicle with a flexible launch date, provided an adequate cost bump, process accommodation, and/or private corporate partnership support doc

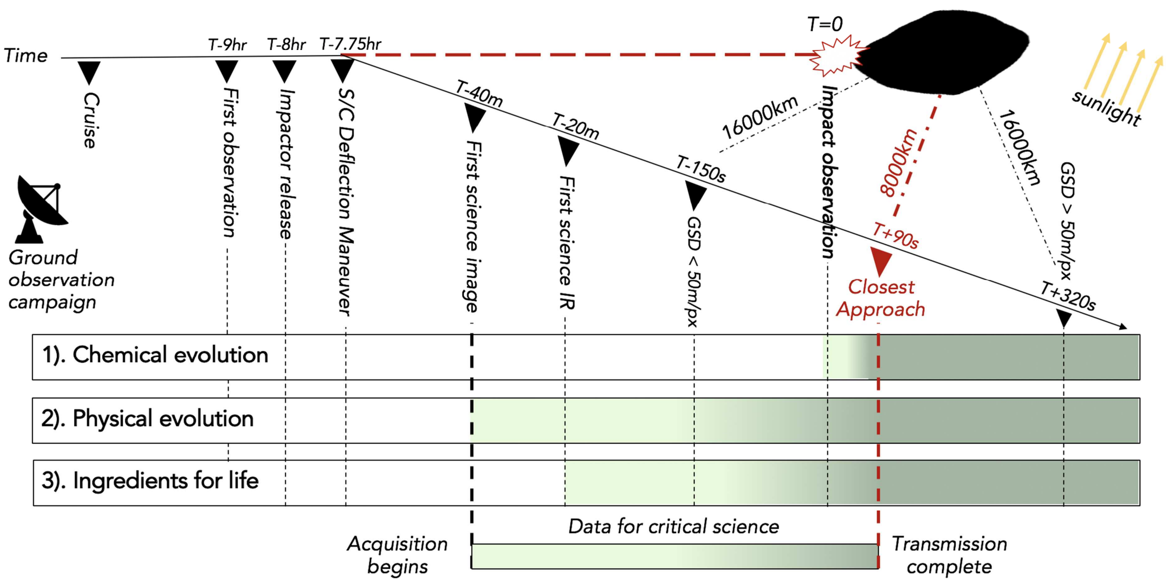


umentation is included.

Ultimately, the quicker a launch can be arranged, the less observational lead time would be necessary, which would reduce mission storage cost and increase the chances of mission success. Thus, to enable a mission like Bridge, the planetary science community must consider advocating for language in the New Frontiers (or other similar AOs) that explicitly allows for purchasing a vehicle with a flexible launch date, storage of the spacecraft, and rapid DSN scheduling.

7. Conclusion

Exploring an exoplanetary system is an incredible scientific opportunity. The most feasible way to accomplish this is to intercept an interstellar object as it passes through our solar system. Such a mission would address multiple high-priority science goals and questions in planetary science and astrophysics, from the formation of solar systems to the development of organic life. We have demonstrated that such a mission is feasible under the NASA New Frontiers cost cap. Our instrument payload has been optimized for a high speed encounter with an ISO and the capability to downlink all mission critical data prior to closest approach. We find that a trajectory design that encounters the ISO in the inner solar system yields the best likelihood for detection and interception of the ISO as well as the optimal environment for data collection. We opt to launch from the ground instead of a parking orbit to reduce potential areas of failure and to maximize delta-v



so that the spacecraft can reach more potential targets. This mission concept pioneers a strategy for a rapid response mission with high scientific return that can be implemented given changes to current announcements of opportunity. A mission like Bridge to visit an ISO would greatly expand the wealth of knowledge generated from the New Frontiers program.

Appendix A

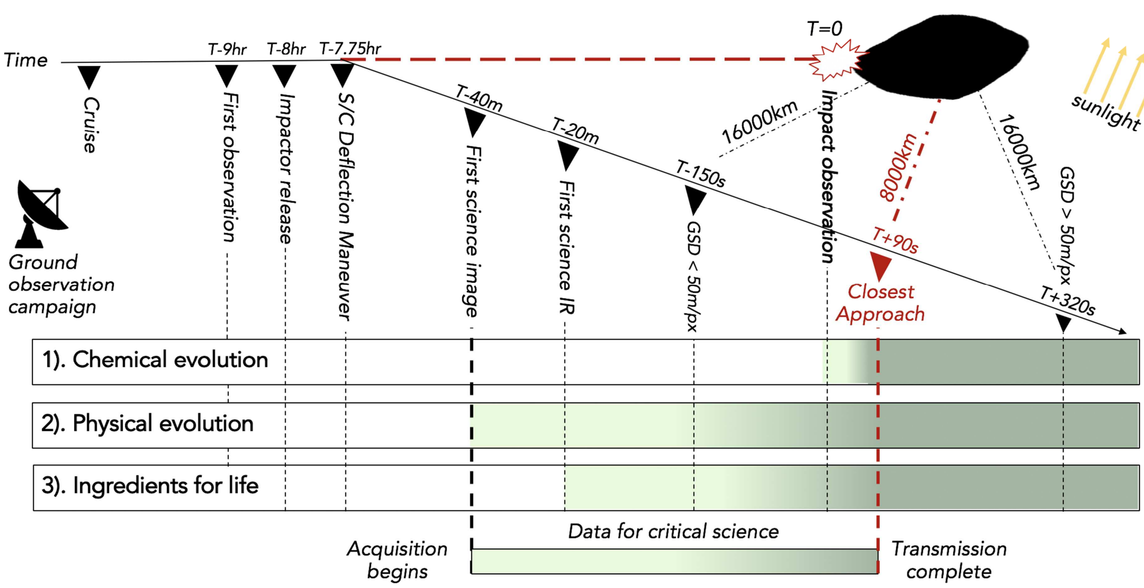
Table A.1 The science traceability matrix

(This content is only available in the online version of the manuscript, due to the oversized nature of the table.)

Appendix B

Here we describe the population statistics of incoming ISOs used in our Monte Carlo analysis in more detail. For each set of encounter criteria, we model 10,000 random ISO trajectories as follows (note that the “bounds” change depending on the specific encounter criteria):

1. Draw a perihelion epoch from a uniform distribution within our mission window (2031-2041)
2. Draw an incoming V_inf from a uniform distribution within the interval [25, 45] km/s
3. Draw a perihelion distance from a uniform distribution within our perihelion bounds
4. **(A. Solar Apex probability distribution):** Draw an incoming right ascension from a Gaussian distribution



(1-sigma = 10*deg) around the solar apex point (lat = 53.43°, lon = 271.79° E). Draw an incoming declination from a Gaussian distribution (1-sigma = 10*deg) around the solar apex point.

(B. Full sky probability distribution): Draw an incoming right ascension and declination using an isotropic probability distribution across the full sky.

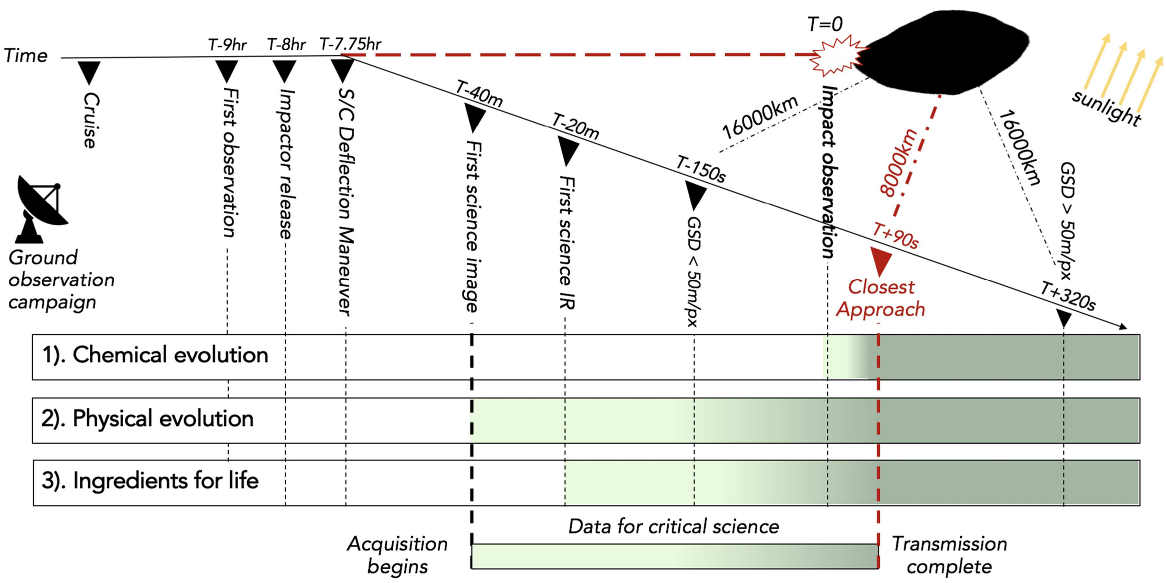
5. Draw a B-plane piercing point angle (theta) from a uniform distribution on the interval [0*deg, 360*deg]

For the purposes of our simplified analysis, all the variables are considered to be independent of one another. In reality, this assumption may not be strictly accurate.

Acknowledgements

The Bridge team would like to thank Leslie Lowes and Joyce Armijo for their coordination of the Planetary Science Summer Seminar, Bill Smythe for his assistance with our instruments and STM, Randii Wessen and the JPL A-Team sessions, Al Nash and Team X for their expertise and guidance. We'd also like to thank NASA Planetary Science Division, and NASA's Radioisotope Power Systems program for financial support of the program. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004). We are also grateful to Dr. Darryl Seligman and an anonymous reviewer for their helpful feedback.

The information presented about the Bridge mission concept is pre-decisional and is provided for planning and discussion purposes only. This document has been reviewed and determined not to contain export controlled technical data.



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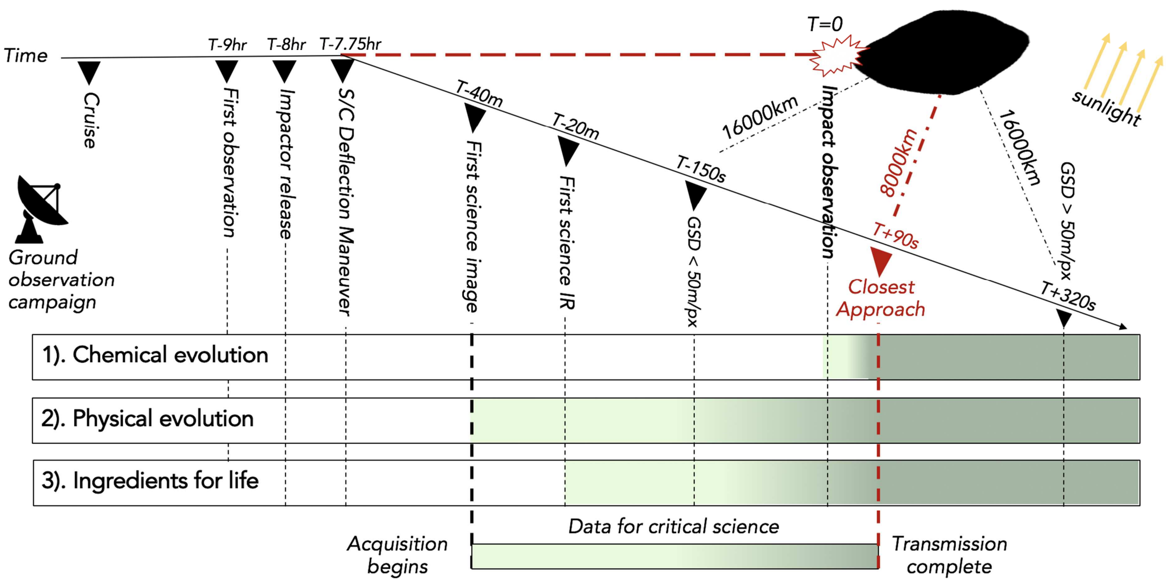

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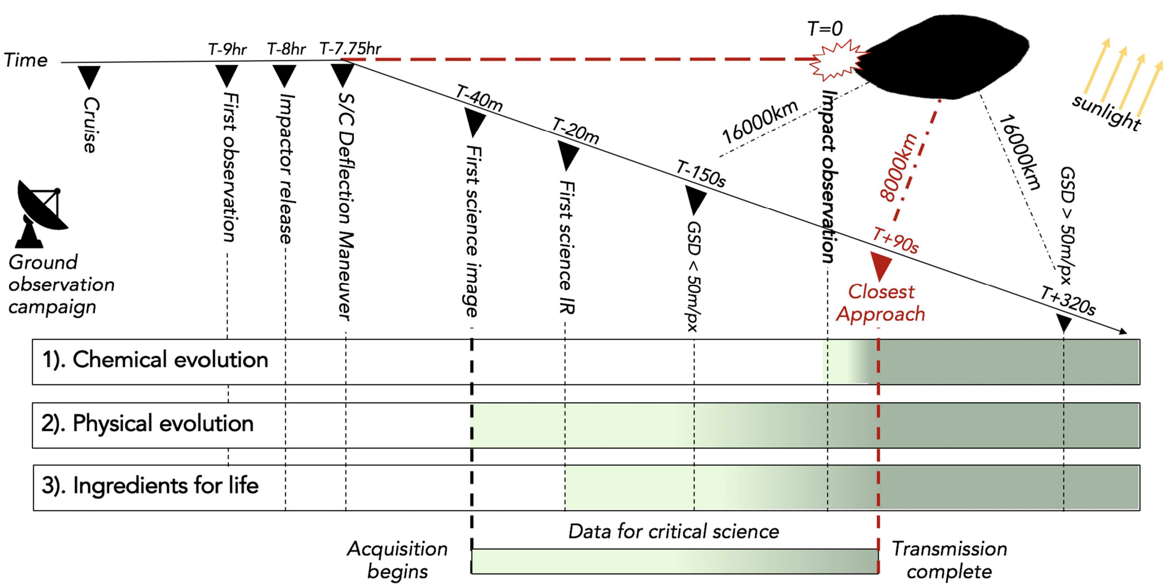

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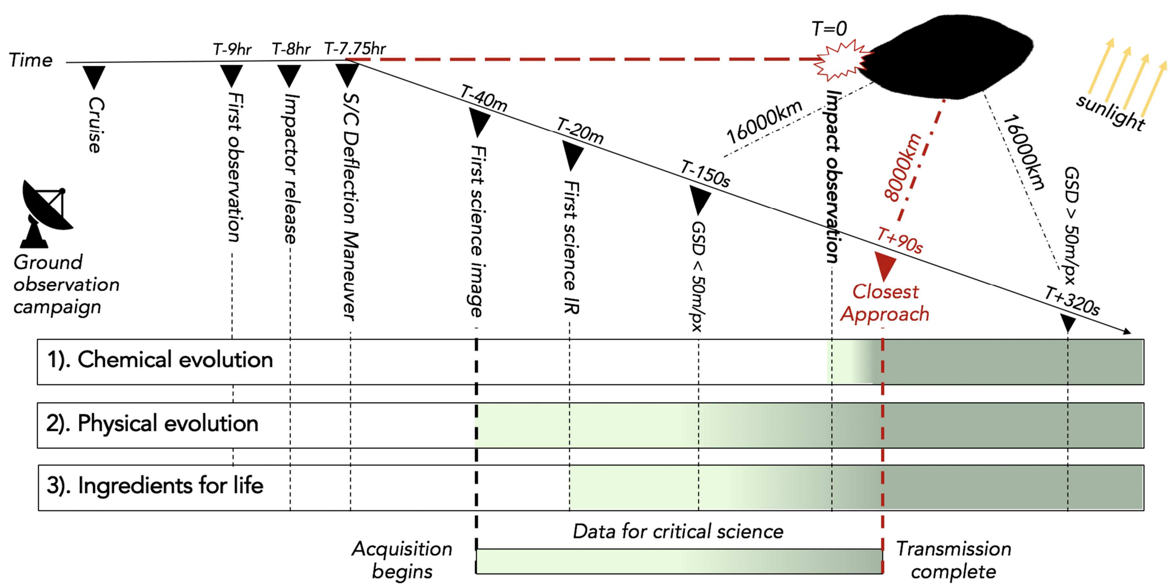

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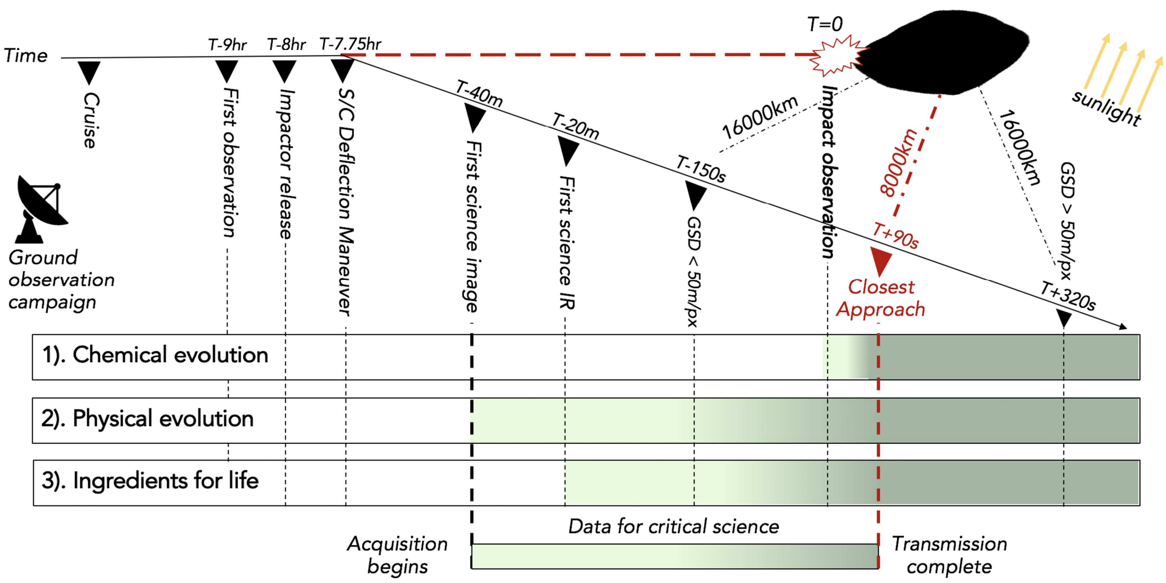

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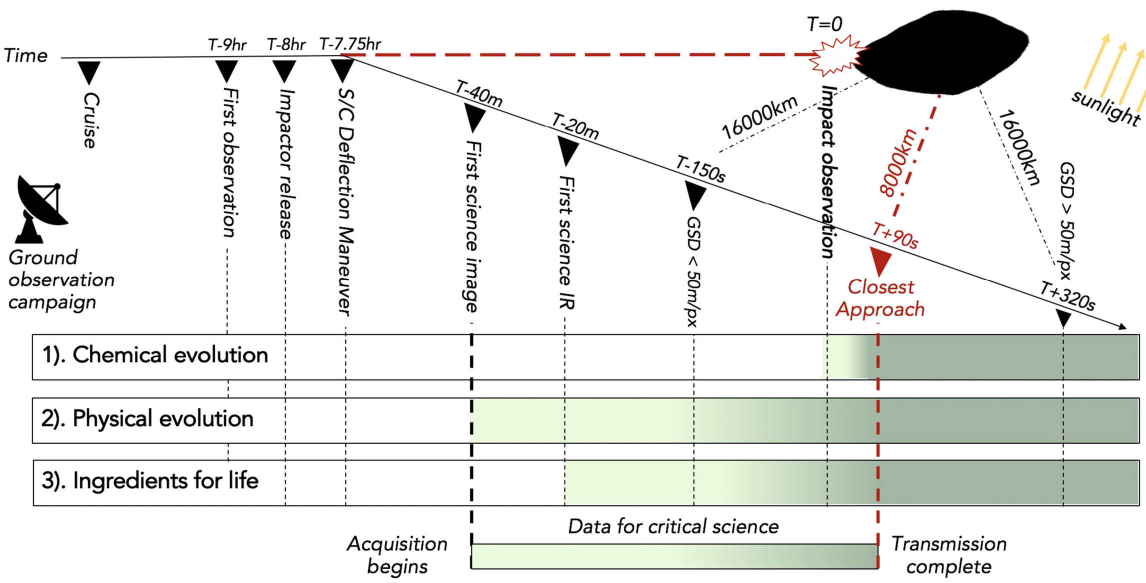

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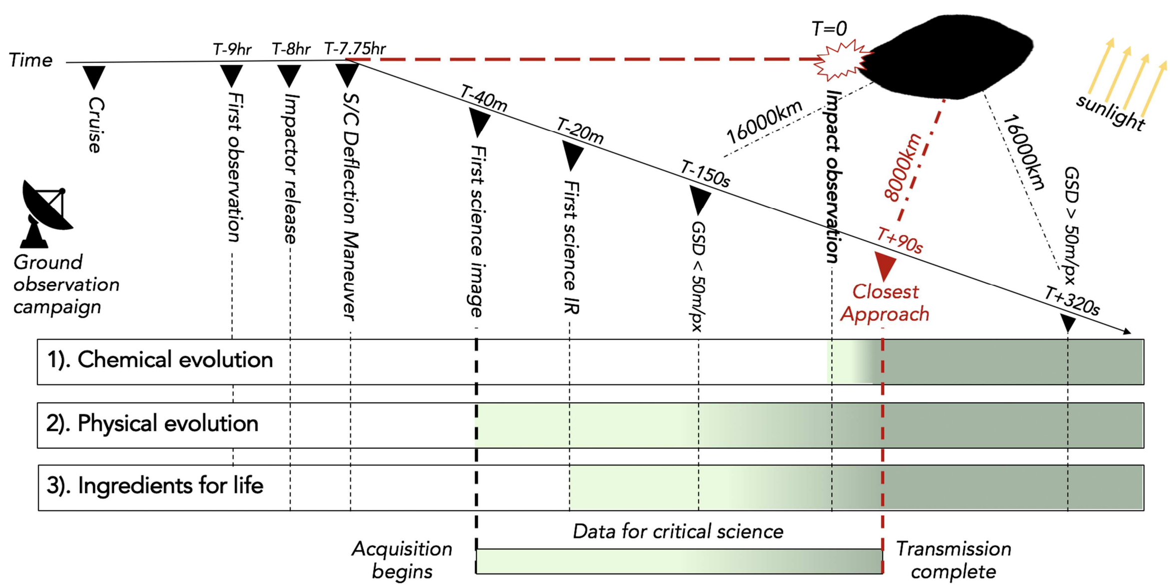

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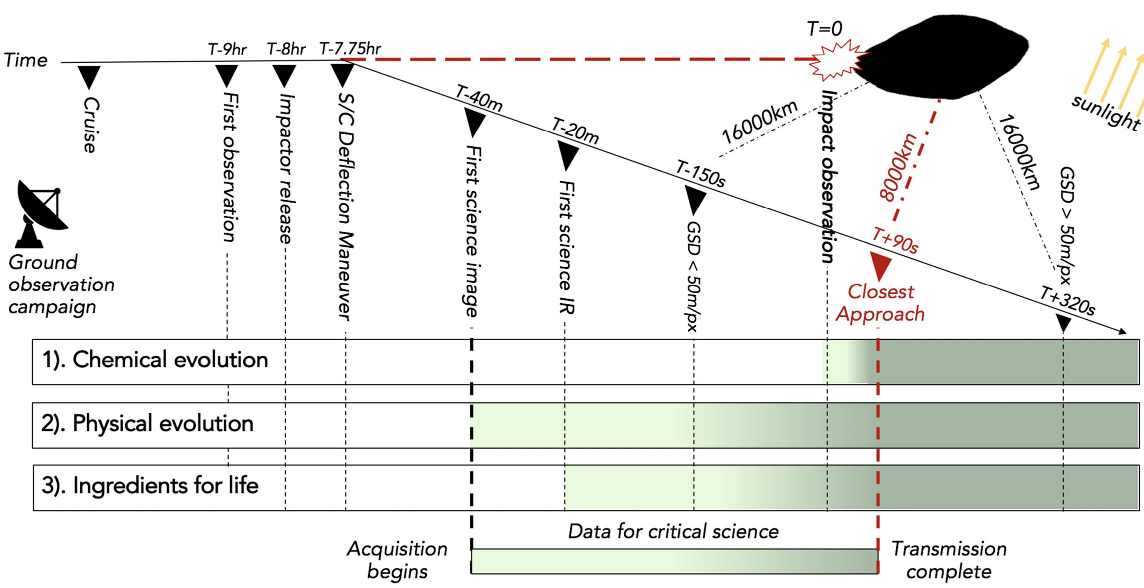

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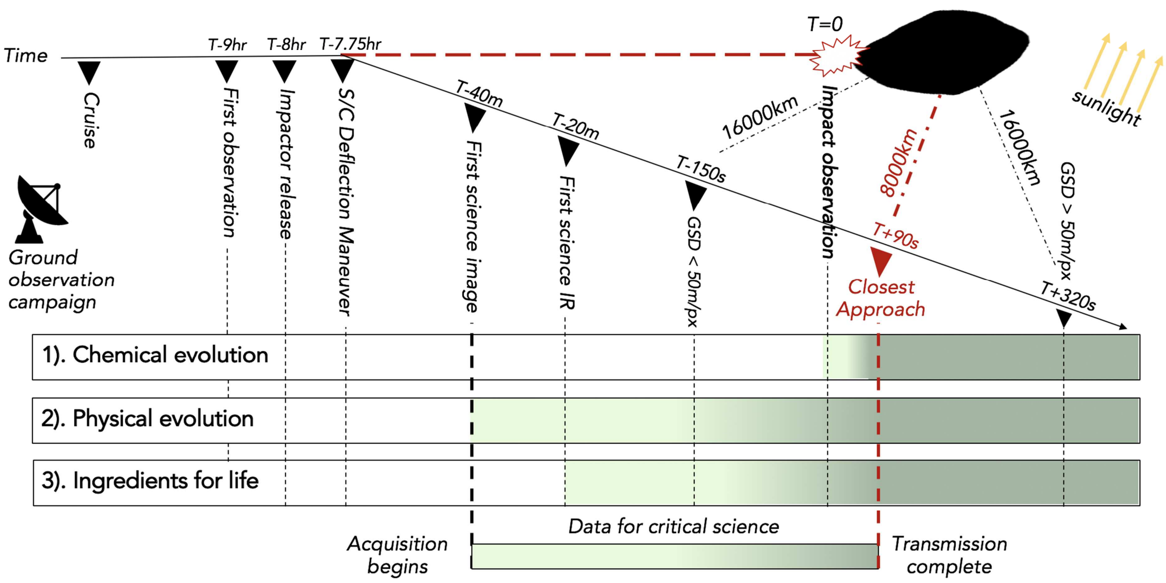

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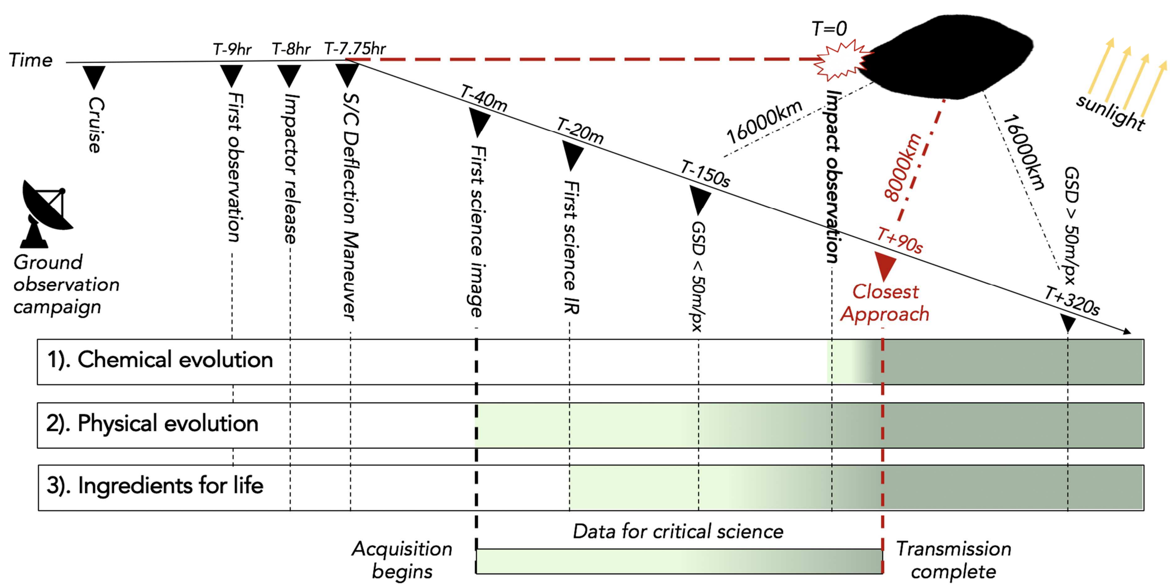

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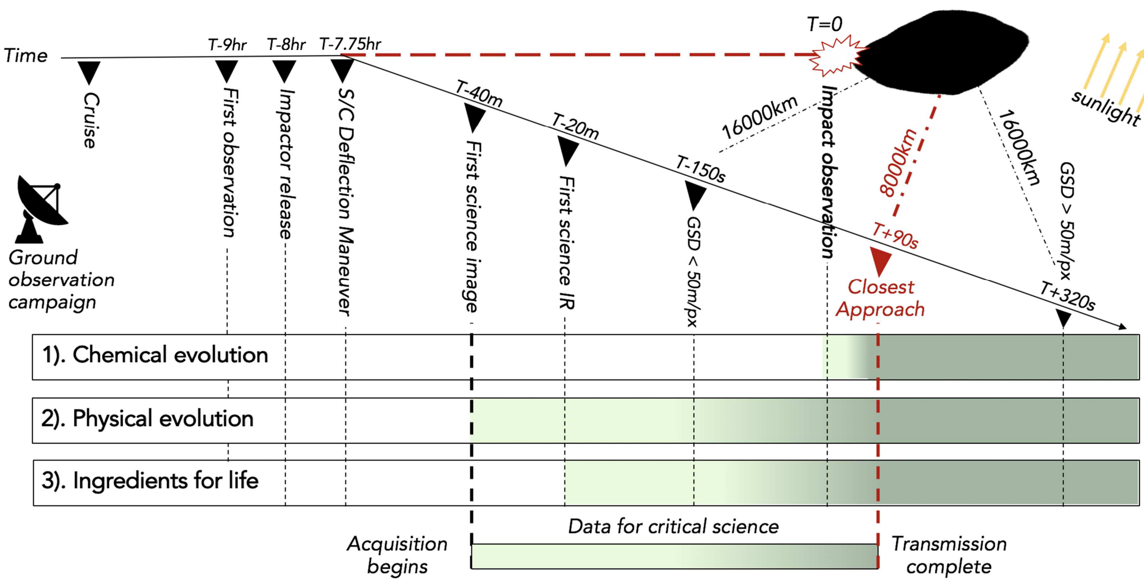

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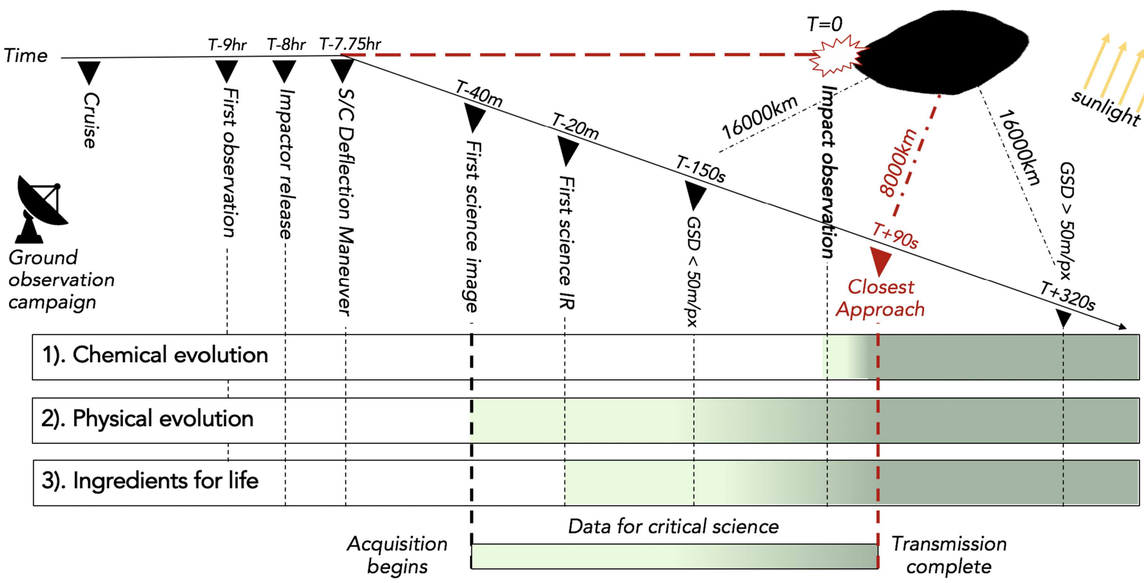

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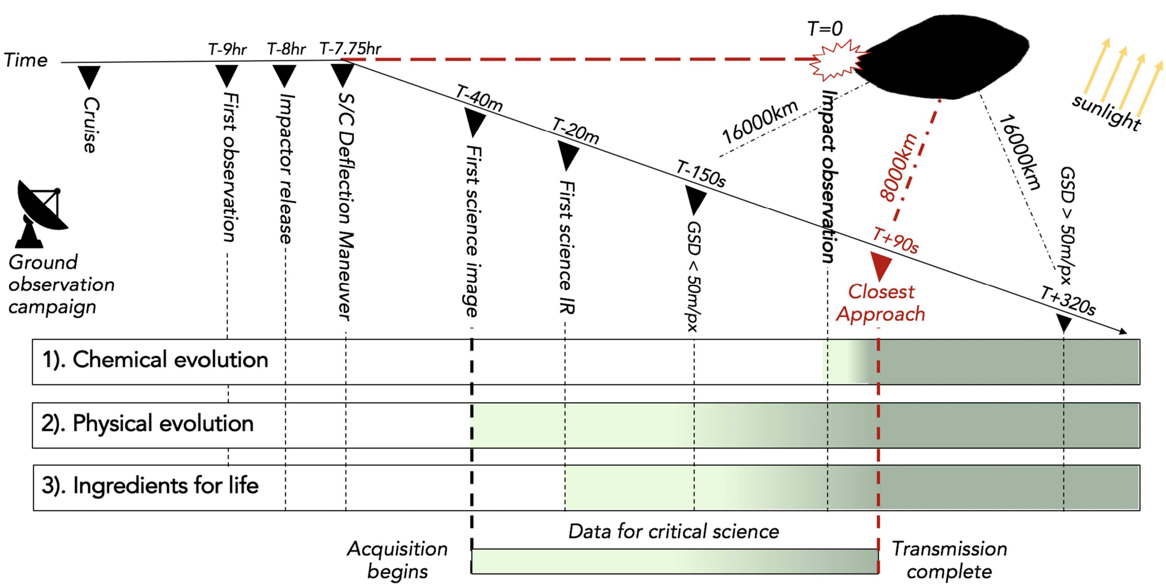

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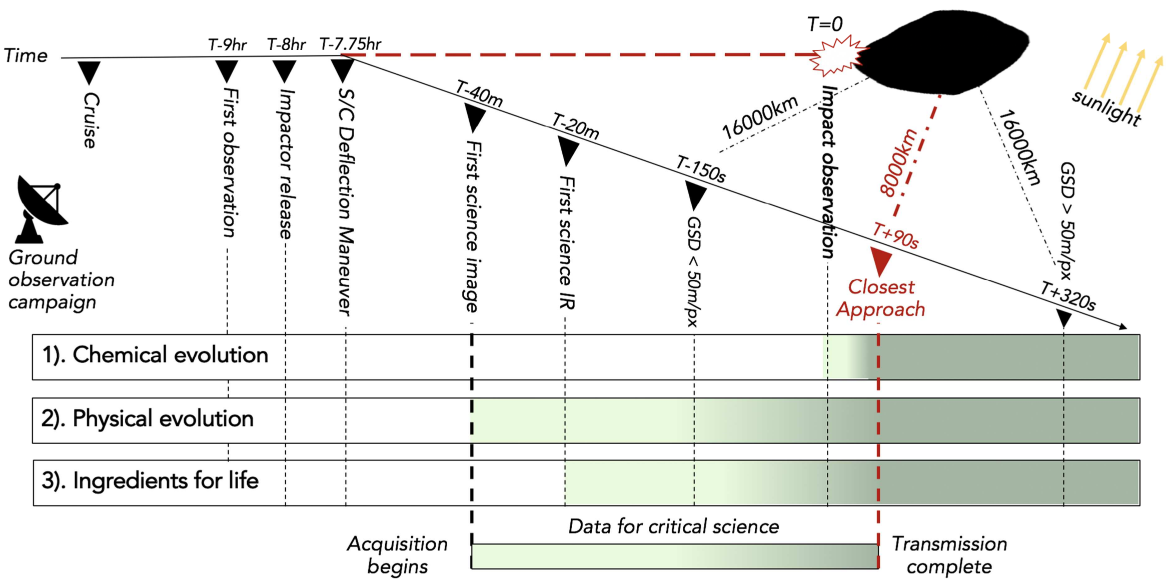

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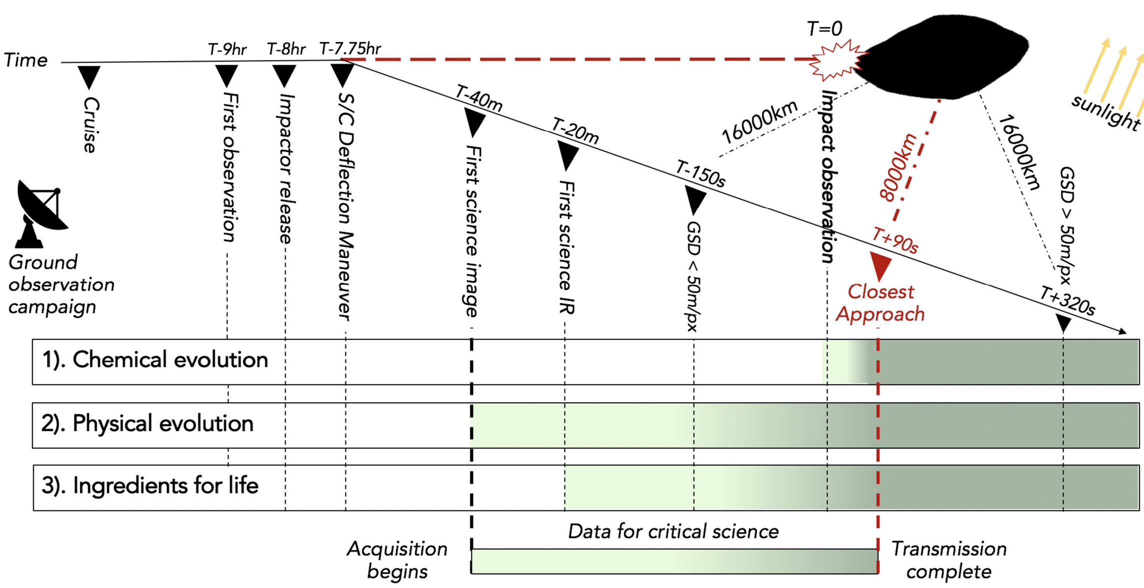

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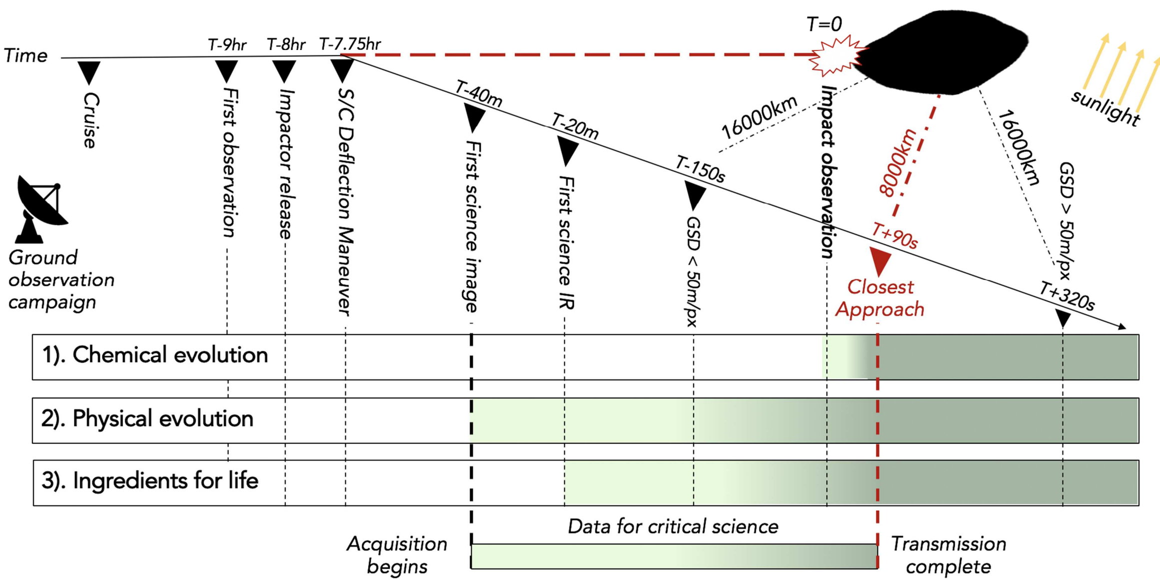

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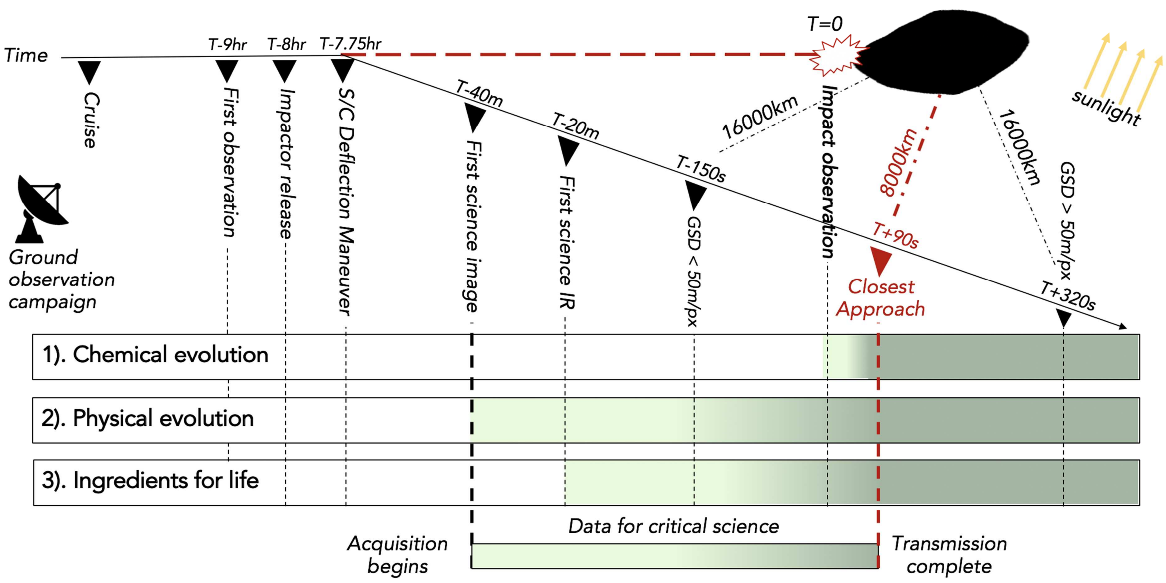

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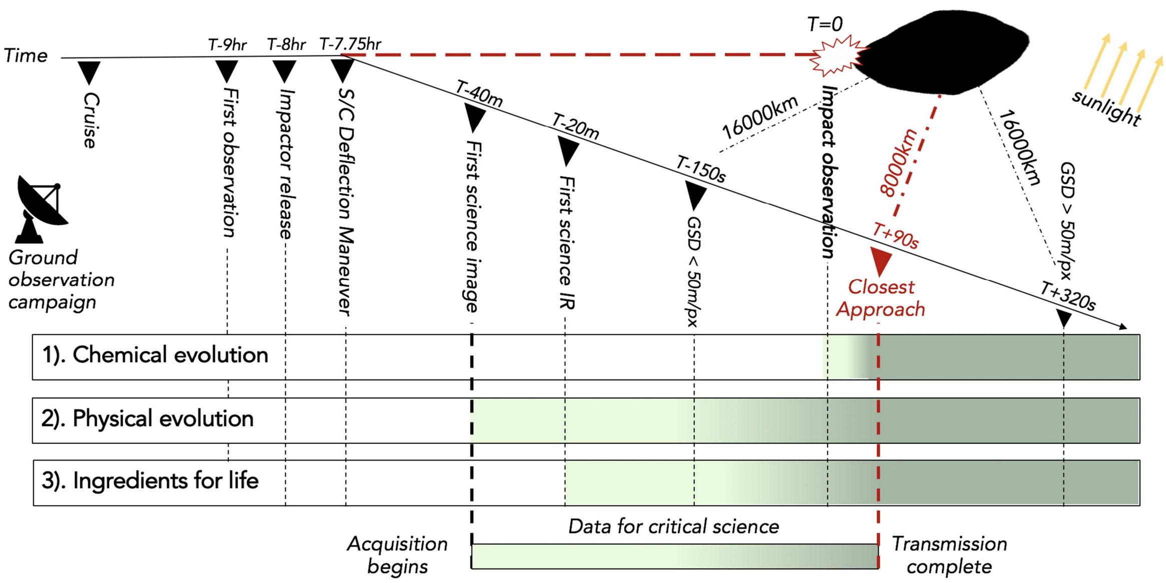

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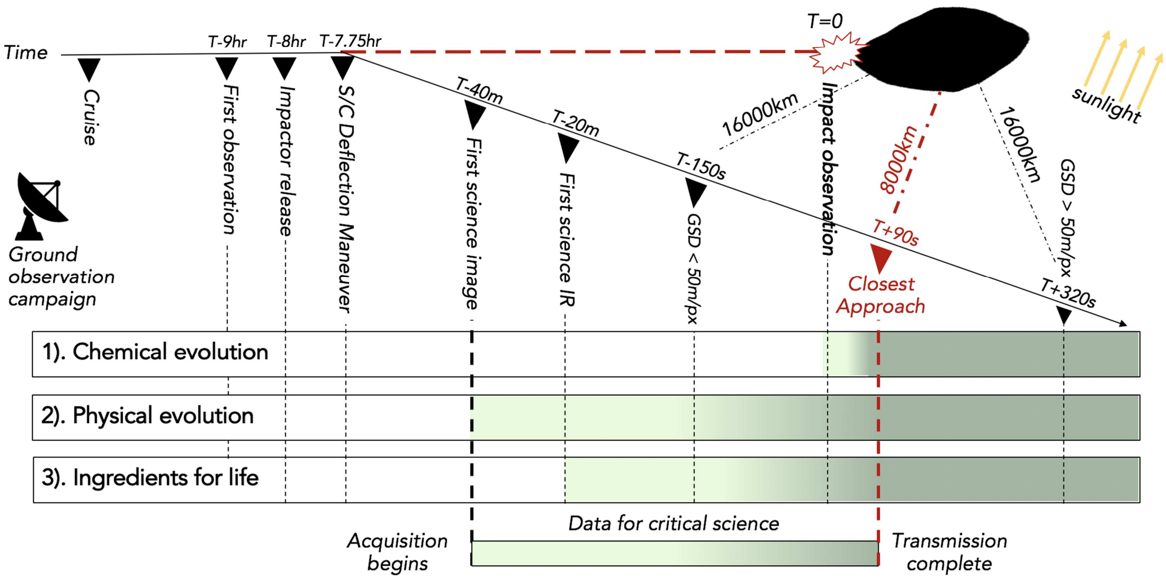


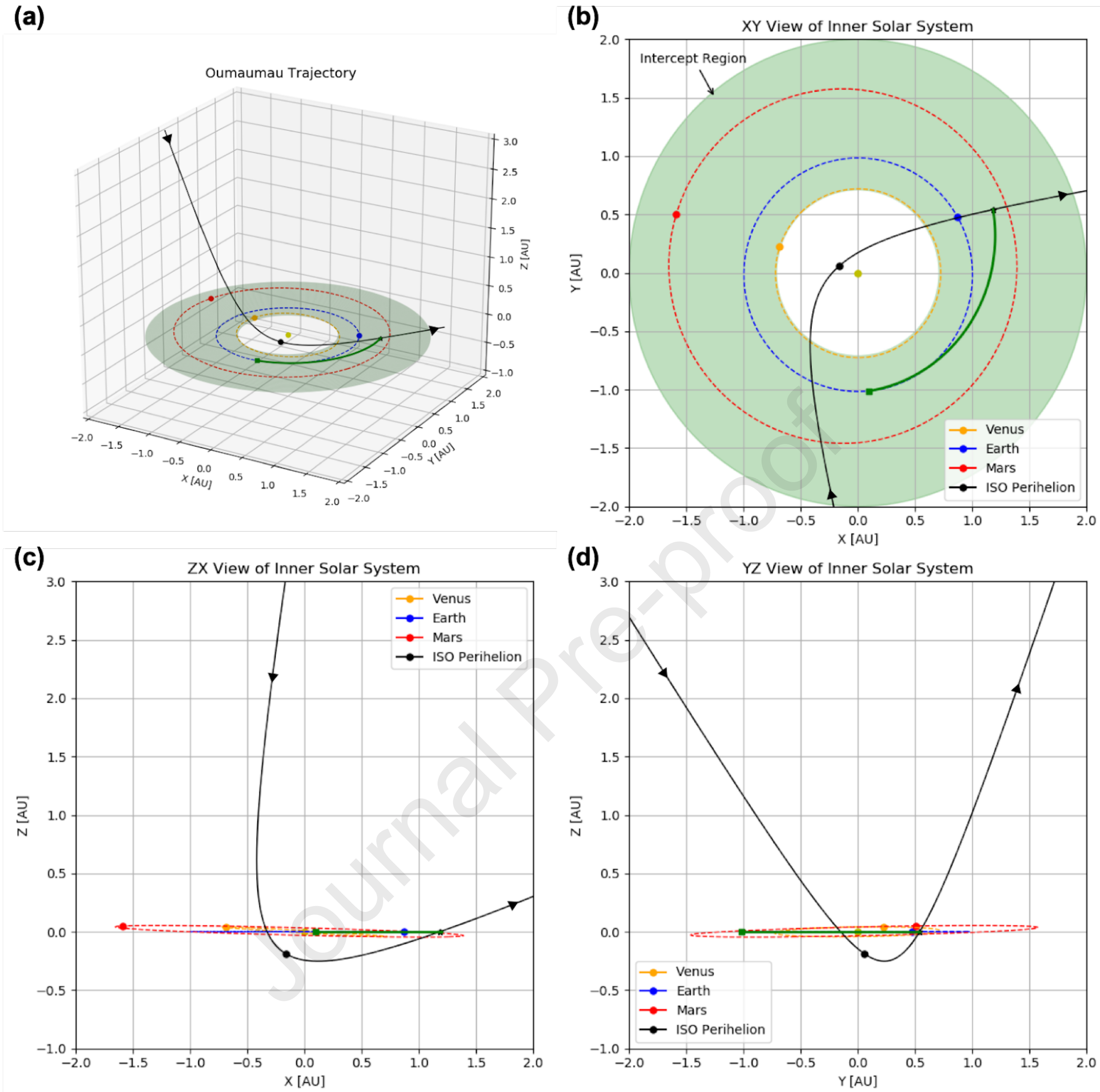
Table 5: Illustration of the Bridge mission trade space

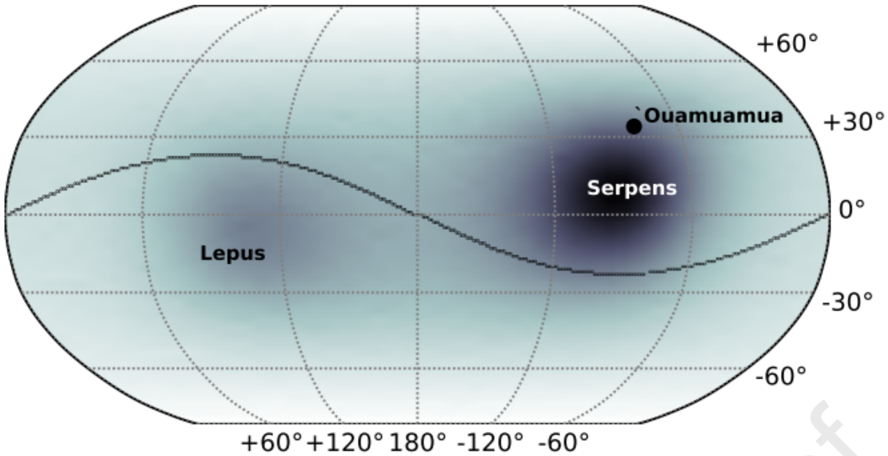
	Mission cases												
	Inner solar system									Outer solar system			
Property	**Baseline (Solar apex)[A]**	**Baseline (full sky)[B]**	**Slow flyby[C]**	**Fast flyby[D]**	**1-year Notice[E]**	**Quicker launch[F]**	**1-year notice, quicker launch[G]**	**3-month notice, immediate launch[H]**	**Wider Bounds[I]**	**Smaller spacecraft[J]**	**Smaller spacecraft (Solar apex)[K]**	**Smaller spacecraft (full sky)[L]**	**Smaller spacecaft, 3-month notice[M]**
ISO statistics	Solar apex	Full sky	Solar apex	Solar apex	Solar apex	Solar apex	Solar apex	Solar apex	Solar apex	Solar apex	Solar apex	Full sky	Solar apex
Encounter V_∞ (km/s)	< 70	< 70	< 40	< 100	< 70	< 70	< 70	< 70	< 70	< 70	< 70	< 70	
Detection lead time (yrs)	2	2	2	2	1	2	1	0.25	2	2	2	2	0.25
Launch delay (days)	180	180	180	180	180	90	90	90	180	180	180	180	180
Encounter distance (AU)	0.7-2	0.7-2	0.7-2	0.7-2	0.7-2	0.7-2	0.7-2.0	0.7-2.0	0.1-3.0	0.7-2	0.7-30	0.7-30	0.7-30
Launch C3 (km^2/s^2)	< 60	< 60	< 60	< 60	< 60	< 60	< 60	< 60	< 60	< 164	< 164	< 164	<164
Single ISO reachability (%)	65.02	65.34	15.54	67.66	22.11	69.47	33.6	6.18	69.87	82.52	85.88	86.63	17.88
7 ISO mission success probability	99.94	99.94	69.34	99.96	82.61	99.98	94.31	36.01	99.98	99.9995	99.9999	99.9999	74.81

[A] This is the nominal spacecraft described by this study, evaluated for ISOs with a Gaussian distribution about the solar apex
[B] This is the nominal spacecraft described by this study, evaluated for ISOs with uniform distribution across the full sky
[C] Enforce a slower relative velocity between the ISO and spacecraft at closest approach
[D] Allow for a higher relative velocity between the ISO and spacecraft at closest approach
[E] Assume less advanced detection capabilities. ISOs are detected closer to their perihelion (1 year or 3 months in advance).
[F] Allow for a faster turnaround time between detection and launch
[G] Combination of the previous two cases
[G] Assumes detection 90 days before the target's perihelion, and an immediate launch upon detection (i.e. the spacecraft is already on the launch pad when the object is detected)
[I] May require redesigning the thermal / power / telecom systems to handle the more extreme encounters (e.g. shielding or additional heating units)
[J] This case uses New Horizon's launch C3. However, this would require significantly redesigning the spacecraft to reduce our mass by ~1/2.
[K] This case uses New Horizon's launch C3 for an outer solar system encounter, evaluated for ISOs with a Gaussian distribution about the solar apex. However, this would require significantly redesigning the spacecraft to reduce our mass by ~1/2.
[L] This case uses New Horizon's launch C3 for an outer solar system encounter, evaluated for ISOs with uniform distribution across the full sky. However, this would require significantly redesigning the spacecraft to reduce our mass by ~1/2.
[M] This case uses New Horizon's launch C3 for an outer solar system encounter, evaluated for ISOs with a Gaussian distribution about the solar apex. However, this would require significantly redesigning the spacecraft to reduce our mass by ~1/2. It also assumes less advanced detection capabilities. ISOs are detected closer to their perihelion (3 months in advance).

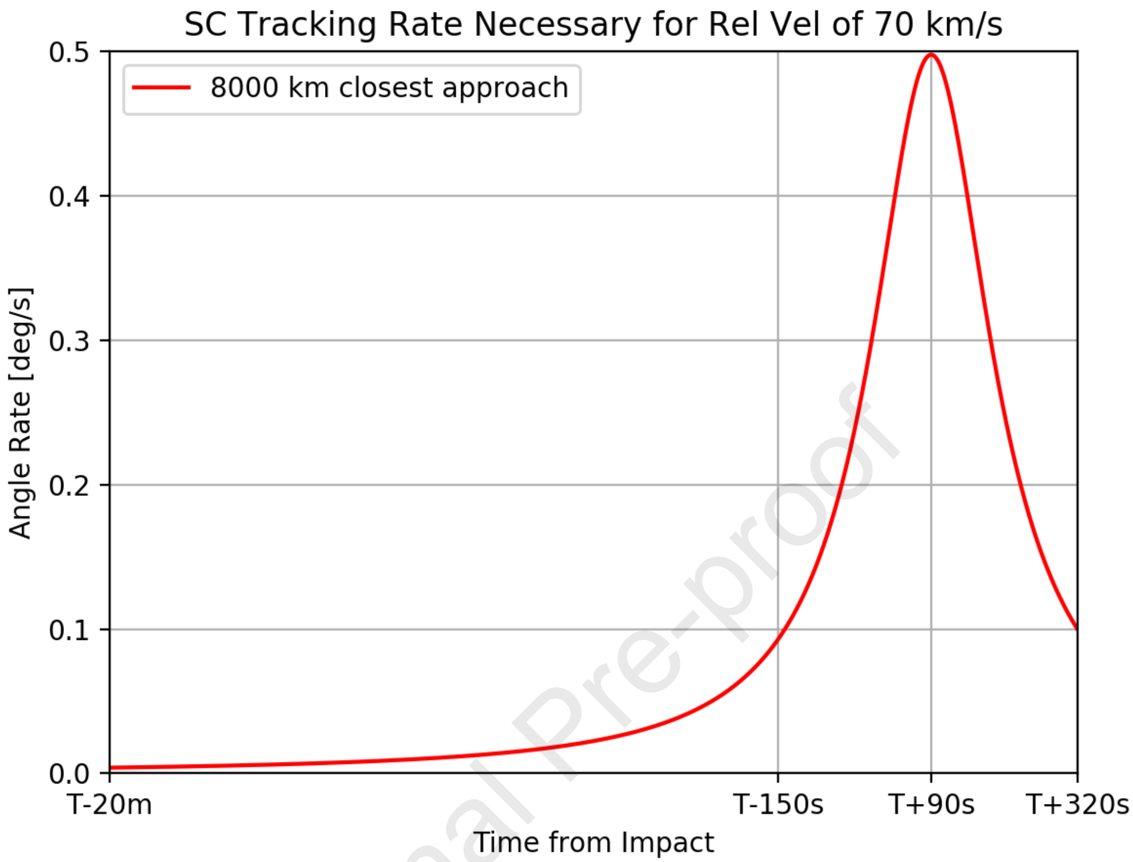
Science Goal	Science Objective	Physical Parameters	Observables	Instrument and Functional Requirements	Projected Performance	Mission Requirements
Determine whether the Solar System evolved like other stellar systems within the Milky Way galaxy (Section 2.1).	Determine whether the ISO formed in an environment with chemical composition similar to the Solar System (Section 2.2.1).	Measurement of $\delta^{17}O$ (McKeegan et al. 2011, Zinner 2014).	312.1 nm (^{16}O), 147.7 nm (^{17}O), 312.1 nm (^{18}O)	UV-visible spectrometer: 307–317 nm spectral range; 0.03 nm spectral resolution; emission greater than 0.1% continuum (Section 3.4)	305–320 nm spectral range; 0.009 nm spectral resolution; emission greater than 0.1% continuum in echelle channel (McClintock et al., 2015, Robert et al., 2016)	Observe at the beginning of the impact through the first 5 seconds of decay. Impact that can be observed by the remote sensing suite with a minimum energy of Deep Impact (Section 4.2.2).
		Atomic abundances (Verchovsky & Sephton 2005, Wieler 2002).	567 nm (Si), 264 and 282 nm (Al), 375 and 238 nm (Fe), 393 and 397 nm (Ca), 314 and 589 nm (Na), 208 nm (K), 518 nm (Mg), 336 and 521 nm (Ti), 403 nm (Mn), 299 nm (Ni)	UV-visible spectrometer: 200–590 nm spectral range; 0.5 nm spectral resolution; emission greater than 1% continuum (Section 3.4)	200–600 nm spectral range; 0.4 nm spectral resolution; emission greater than 0.1% continuum (McClintock et al., 2015, Robert et al., 2016)	
		Relative abundances of noble gases (Verchovsky & Sephton 2005, Wieler 2002).	588 nm (He), 540 and 585 nm (Ne), 459 and 473 nm (Ar), 557 nm (Kr), and 481 and 492 nm (Xe)	UV-visible spectrometer: 450–590 nm spectral range; 0.5 nm spectral resolution; emission greater than 1% continuum (Section 3.4)		
	Determine whether the ISO physically resembles known classes of objects within the Solar System (Section 2.2.2).	Spectral identification of rocks and ices (Meierhenrich et al., 2014).	1.6, 1.4, 2.0, and 2.7 μm (CO_2 ice); 1.05, 1.3, 1.55, 1.65, 2.0, and 3.1 μm (H_2O ice); 2.0, 2.1, and 3.0 μm (NH_3 ice); 1.0, 1.65, 1.82, and 2.2 μm (CH_4 ice); 2.15 μm (N_2 ice)	Near-IR spectrometer: 1.0–3.2 μm spectral range; 0.02 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.2)	1–4 μm spectral range; 0.01 μm spectral resolution; absorptions greater than 0.75% (Reuter et al., 2018)	0.3 mrad control (to keep object in field of view). Launch within six months of detection of the ISO(Section 4.2.1).
			1.0 μm (olivine), 2.0 μm (pyroxene), 1.0–1.5 μm (plagioclase)	Near-IR spectrometer: 1.0–2.2 μm spectral range; 0.02 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.2)		
		Molar abundances of minerals (Asphaug et al., 2006, Asphaug 2009).	9.7–10.6 μm (plagioclase)	Mid-IR spectrometer: 9.5–10.8 μm spectral range; 0.05 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.3)	5–15 μm spectral range; 0.01 μm spectral resolution; absorptions greater than 0.75% (Reuter et al., 2018)	Observe at the beginning of the impact through the first 5 seconds of decay. Impact that can be observed by the remote sensing suite with a minimum energy of Deep Impact (Section 4.2.2).
			9.0–9.8 and 10–12 μm (clinopyroxene)	Mid-IR spectrometer: 8.3–10.5 μm spectral range; 0.02 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.3)		
			9.5–12.0 μm (olivine)	Mid-IR spectrometer: 9.0–12.0 μm spectral range; 0.1 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.3)		
			13.1 μm (oxides)	Mid-IR spectrometer: 12.0–14.0 μm spectral range; 0.02 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.3)		
		Bulk morphological properties of the ISO to 10 m resolution (Asphaug 2009, Meierhenrich et al., 2014).	Intensity and its variation between 350–850 nm.	Spacecraft camera: 25 m/pixel at closest approach (Section 3.1)	20 m/pixel at closest approach (Cheng et al., 2009, Hampton et al., 2005)	0.3 mrad control (to keep object in field of view). Launch within six months of detection of the ISO. Camera slew of 0.43 deg/sec at closest approach (Section 4.2.1).
Determine whether the basic chemical ingredients for life travel between stellar systems. (Section 2.1).	Determine whether the ISO contains prebiotic ingredients (Section 2.2.3).	The presence of functional groups of organic matter. PAHs and tholins are particularly interesting for their biological and space weathering implications (Meierhenrich et al., 2014).	7.4 μm (aliphatic), 12.5 μm (unsaturated), 7–14 μm (PAH), 7.4 μm (oxygen groups), 6.5 μm (nitrogen groups), 7.1 μm (ketones and carbonyl)	Mid-IR spectrometer: 5–14 μm spectral range; 0.02 μm spectral resolution; absorptions >1% in reflectance (Section 3.3)	5–15 μm spectral range; 0.01 μm spectral resolution; absorptions >0.75% in reflectance (Reuter et al., 2018)	0.3 mrad control (to keep object in field of view). Launch within six months of detection of the ISO (Section 4.2.1).
			5.3 μm (tholins)			
			3.2–3.4 μm (C-H), 1.6 and 2.5 μm (O-H), 2.2 μm (N_2)	Near-IR spectrometer: 1.6–3.2 μm spectral range; 0.02 μm spectral resolution; absorptions >1% in reflectance (Section 3.2)	1–4 μm spectral range; 0.01 μm spectral resolution; absorptions >0.75% in reflectance (Reuter et al., 2018)	
		The presence of OH, CH, and N_2 (Meierhenrich et al., 2014).	2.7–2.8 μm (O-H)			
		The abundance of N, P, and S relative to O (Meierhenrich et al., 2014).	400 nm (N), 254 nm (P), 420 nm (S), 278 nm (O)	UV-visible spectrometer: 250–425 nm spectral range; 1 nm spectral resolution; emission >1% continuum (Section 3.4)	200–600 nm spectral range; 0.4 nm spectral resolution; emission >0.1% continuum (McClintock et al., 2015, Robert et al., 2016)	Observe at the beginning of the impact through the first 5 seconds of decay. Impact that can be observed by the remote sensing suite with a minimum energy of Deep Impact (Section 4.2.2).

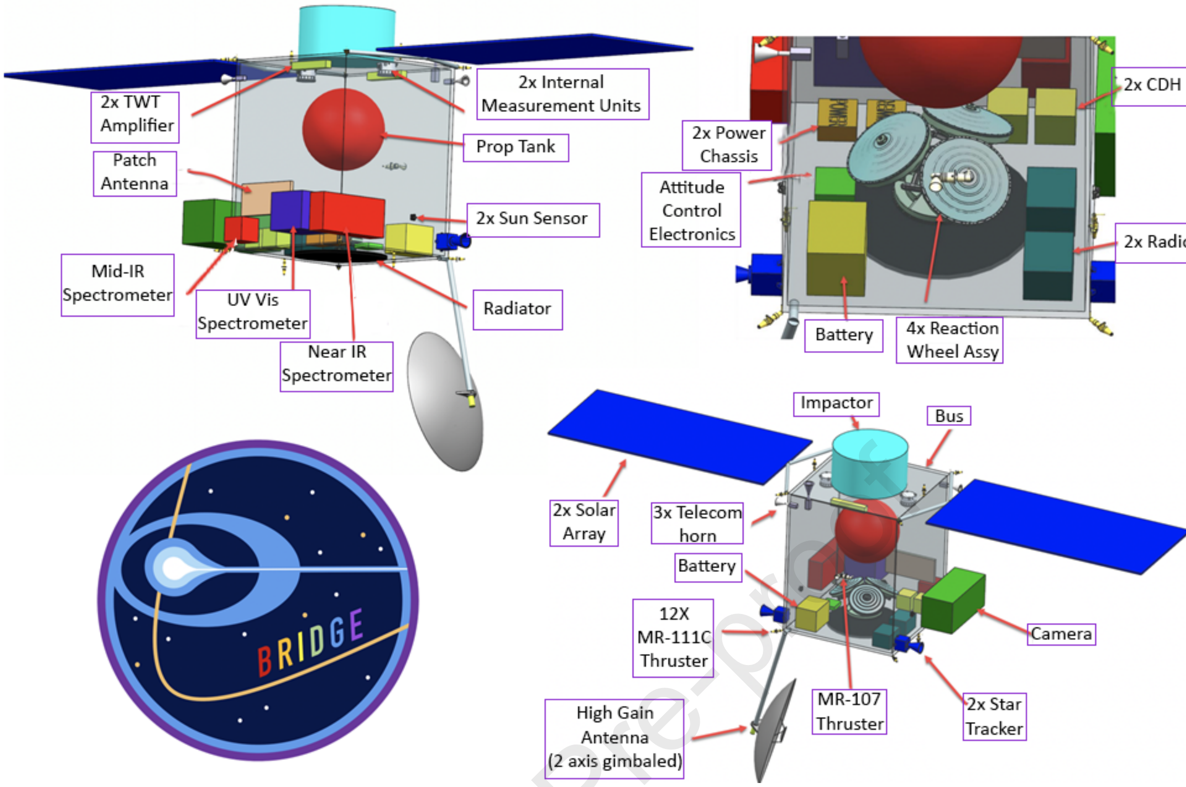
Science Goal	Science Obj				d Performance	Mission Requirements
Determine whether the Solar System evolved like other stellar systems within the Milky Way galaxy (Section 2.1).	Determine whether the ISO formed in an environment with chemical composition similar to the Solar System (Section 2.2.1).	Measurement of $\delta^{17}O$ (McKeegan et al. 2011, Zinner 2014).	312.1 nm (^{16}O), 147.7 nm (^{17}O), 312.1 nm (^{18}O)	UV-visible spectrometer: 307–317 nm spectral range; 0.03 nm spectral resolution; emission greater than 0.1% continuum (Section 3.4)	305–320 nm spectral range; 0.009 nm spectral resolution; emission greater than 0.1% continuum in echelle channel (McClintock et al., 2015, Robert et al., 2016)	Observe at the beginning of the impact through the first 5 seconds of decay. Impact that can be observed by the remote sensing suite with a minimum energy of Deep Impact (Section 4.2.2).
		Atomic abundances (Verchovsky & Sephton 2005, Wieler 2002).	567 nm (Si), 264 and 282 nm (Al), 375 and 238 nm (Fe), 393 and 397 nm (Ca), 314 and 589 nm (Na), 208 nm (K), 518 nm (Mg), 336 and 521 nm (Ti), 403 nm (Mn), 299 nm (Ni)	UV-visible spectrometer: 200–590 nm spectral range; 0.5 nm spectral resolution; emission greater than 1% continuum (Section 3.4)	200–600 nm spectral range; 0.4 nm spectral resolution; emission greater than 0.1% continuum (McClintock et al., 2015, Robert et al., 2016)	
		Relative abundances of noble gases (Verchovsky & Sephton 2005, Wieler 2002).	588 nm (He), 540 and 585 nm (Ne), 459 and 473 nm (Ar), 557 nm (Kr), and 481 and 492 nm (Xe)	UV-visible spectrometer: 450–590 nm spectral range; 0.5 nm spectral resolution; emission greater than 1% continuum (Section 3.4)		
	Determine whether the ISO physically resembles known classes of objects within the Solar System (Section 2.2.2).	Spectral identification of rocks and ices (Meierhenrich et al., 2014).	1.6, 1.4, 2.0, and 2.7 μm (CO_2 ice); 1.05, 1.3, 1.55, 1.65, 2.0, and 3.1 μm (H_2O ice); 2.0, 2.1, and 3.0 μm (NH_3 ice); 1.0, 1.65, 1.82, and 2.2 μm (CH_4 ice); 2.15 μm (N_2 ice)	Near-IR spectrometer: 1.0–3.2 μm spectral range; 0.02 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.2)	1–4 μm spectral range; 0.01 μm spectral resolution; absorptions greater than 0.75% (Reuter et al., 2018)	0.3 mrad control (to keep object in field of view). Launch within six months of detection of the ISO(Section 4.2.1).
			1.0 μm (olivine), 2.0 μm (pyroxene), 1.0–1.5 μm (plagioclase)	Near-IR spectrometer: 1.0–2.2 μm spectral range; 0.02 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.2)		
		Molar abundances of minerals (Asphaug et al., 2006, Asphaug 2009).	9.7–10.6 μm (plagioclase)	Mid-IR spectrometer: 9.5–10.8 μm spectral range; 0.05 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.3)	5–15 μm spectral range; 0.01 μm spectral resolution; absorptions greater than 0.75% (Reuter et al., 2018)	Observe at the beginning of the impact through the first 5 seconds of decay. Impact that can be observed by the remote sensing suite with a minimum energy of Deep Impact (Section 4.2.2).
			9.0–9.8 and 10–12 μm (clinopyroxene)	Mid-IR spectrometer: 8.3–10.5 μm spectral range; 0.02 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.3)		
			9.5–12.0 μm (olivine)	Mid-IR spectrometer: 9.0–12.0 μm spectral range; 0.1 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.3)		
			13.1 μm (oxides)	Mid-IR spectrometer: 12.0–14.0 μm spectral range; 0.02 μm spectral resolution; absorptions greater than 1% in reflectance (Section 3.3)		
		Bulk morphological properties of the ISO to 10 m resolution (Asphaug 2009, Meierhenrich et al., 2014).	Intensity and its variation between 350–850 nm.	Spacecraft camera: 25 m/pixel at closest approach (Section 3.1)	20 m/pixel at closest approach (Cheng et al., 2009, Hampton et al., 2005)	0.3 mrad control (to keep object in field of view). Launch within six months of detection of the ISO. Camera slew of 0.43 deg/sec at closest approach (Section 4.2.1).
Determine whether the basic chemical ingredients for life travel between stellar systems. (Section 2.1).	Determine whether the ISO contains prebiotic ingredients (Section 2.2.3).	The presence of functional groups of organic matter. PAHs and tholins are particularly interesting for their biological and space weathering implications (Meierhenrich et al., 2014).	7.4 μm (aliphatic), 12.5 μm (unsaturated), 7–14 μm (PAH), 7.4 μm (oxygen groups), 6.5 μm (nitrogen groups), 7.1 μm (ketones and carbonyl)	Mid-IR spectrometer: 5–14 μm spectral range; 0.02 μm spectral resolution; absorptions >1% in reflectance (Section 3.3)	5–15 μm spectral range; 0.01 μm spectral resolution; absorptions >0.75% in reflectance (Reuter et al., 2018)	0.3 mrad control (to keep object in field of view). Launch within six months of detection of the ISO (Section 4.2.1).
			5.3 μm (tholins)			
			3.2–3.4 μm (C-H), 1.6 and 2.5 μm (O-H), 2.2 μm (N_2)	Near-IR spectrometer: 1.6–3.2 μm spectral range; 0.02 μm spectral resolution; absorptions >1% in reflectance (Section 3.2)	1–4 μm spectral range; 0.01 μm spectral resolution; absorptions >0.75% in reflectance (Reuter et al., 2018)	
		The presence of OH, CH, and N_2 (Meierhenrich et al., 2014).	2.7–2.8 μm (O-H)			
		The abundance of N, P, and S relative to O (Meierhenrich et al., 2014).	400 nm (N), 254 nm (P), 420 nm (S), 278 nm (O)	UV-visible spectrometer: 250–425 nm spectral range; 1 nm spectral resolution; emission >1% continuum (Section 3.4)	200–600 nm spectral range; 0.4 nm spectral resolution; emission >0.1% continuum (McClintock et al., 2015, Robert et al., 2016)	Observe at the beginning of the impact through the first 5 seconds of decay. Impact that can be observed by the remote sensing suite with a minimum energy of Deep Impact (Section 4.2.2).

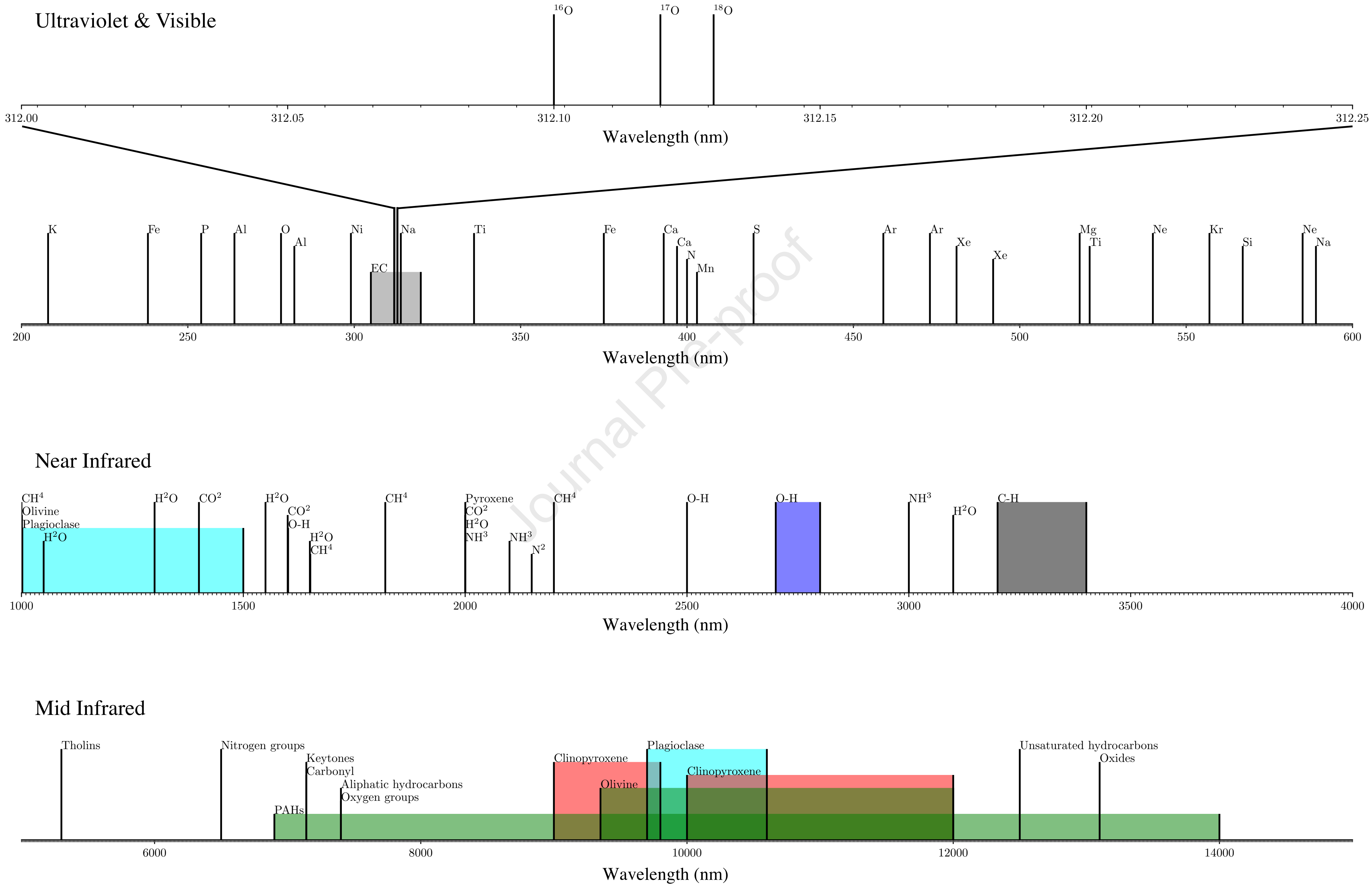

(a)
Oumaumau Trajectory
X [AU]
Y [AU]
Z [AU]
(b)
XY View of Inner Solar System
Intercept Region
Venus
Earth
Mars
ISO Perihelion
X [AU]
Y [AU]
(c)
ZX View of Inner Solar System
Venus
Earth
Mars
ISO Perihelion
X [AU]
Z [AU]
(d)
YZ View of Inner Solar System
Venus
Earth
Mars
ISO Perihelion
Y [AU]
Z [AU]



`Ouamuamua
Serpens
Lepus
+60°
+30°
0°
-30°
-60°
+60°
+120°
180°
-120°
-60°


SC Tracking Rate Necessary for Rel Vel of 70 km/s
8000 km closest approach
Angle Rate [deg/s]
0.5
0.4
0.3
0.2
0.1
0.0
T-20m
T-150s
T+90s
T+320s
Time from Impact


2x TWT Amplifier
Patch Antenna
Mid-IR Spectrometer
UV Vis Spectrometer
Near IR Spectrometer
2x Internal Measurement Units
Prop Tank
2x Sun Sensor
Radiator
2x Power Chassis
Attitude Control Electronics
Battery
4x Reaction Wheel Assy
2x CDH
2x Radios
BRIDGE
Impactor
Bus
2x Solar Array
3x Telecom horn
Battery
12X MR-111C Thruster
High Gain Antenna (2 axis gimbaled)
MR-107 Thruster
2x Star Tracker
Camera


Ultraviolet & Visible
16O
17O
18O
312.00
312.05
312.10
312.15
312.20
312.25
Wavelength (nm)
K
Fe
P
Al
O
Al
Ni
EC
Na
Ti
Fe
Ca
Ca
N
Mn
S
Ar
Ar
Xe
Xe
Mg
Ti
Ne
Kr
Si
Ne
Na
200
250
300
350
400
450
500
550
600
Wavelength (nm)
Near Infrared
CH4
Olivine
Plagioclase
H2O
H2O
CO2
H2O
CO2
O-H
H2O
CH4
CH4
Pyroxene
CO2
H2O
NH3
NH3
N2
CH4
O-H
O-H
NH3
H2O
C-H
1000
1500
2000
2500
3000
3500
4000
Wavelength (nm)
Mid Infrared
Tholins
Nitrogen groups
Keytones
Carbonyl
Aliphatic hydrocarbons
Oxygen groups
PAHs
Clinopyroxene
Olivine
Plagioclase
Clinopyroxene
Unsaturated hydrocarbons
Oxides
6000
8000
10000
12000
14000
Wavelength (nm)

Highlights for

"Bridge to the stars: A mission concept to an interstellar object"

- Interstellar objects allow up-close study of exoplanetary systems during our lifetime
- These fast targets present challenges for traditional mission architectures
- We present a detailed mission concept to a yet-to-be-discovered interstellar object
- The spacecraft features a remote sensing payload with a guided impactor
- The spacecraft must be launched within 3-6 months of target discovery

Declaration of interests

☑ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: